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EVALUATING THE ROLE OF UNMANNED AERIAL VEHICLES TO ENHANCE CONSTRUCTION PROJECT PRODUCTIVITY

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Abstract. The construction industry, generating significant goods and services annually, remains one of the least digitalized sectors globally, with Malaysia's construction industry particularly dependent on manual labor. This study investigates the implementation opportunities and challenges of Unmanned Aerial Vehicles (UAVs) in Malaysia's construction industry to enhance productivity and efficiency. Through a mixed-method approach, the research combines qualitative data from 20 semi-structured interviews with quantitative analysis of 200 survey responses from construction professionals. Structural Equation Modeling identified four key opportunity categories: Site Surveying, Site Inspection, Constructing and Repairing, and Enhancing Manpower, Materials, and Machinery (3M) Coordination. The analysis revealed that Constructing and Repairing (0.62) showed the strongest influence on UAVs implementation, followed by Enhancing 3M Coordination (0.61). Five primary challenges were identified: Safety Concerns (0.74), Cost Challenges (0.69), Technical Difficulties (0.61), Regulation Factors (0.53), and Environmental Factors (0.47). The study developed a comprehensive framework for UAVs implementation in construction, highlighting critical success factors and barriers. Future research opportunities include investigating long-term economic impacts through longitudinal case studies and examining UAVs integration with Building Information Modeling systems and Radio-Frequency Identification to optimize technological coordination between aerial data collection and digital modeling.

Keywords: Unmanned Aerial Vehicles, construction productivity, UAVs challenges, Malaysia's construction industry, technology adoption.

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1. Introduction

With $10 trillion worth of construction-related goods and services produced annually, the construction industry is acknowledged as one of the top revenue-generating industries in the world (Chen et al., 2021). However, the construction sector is the least digitalized industries globally (De Winter et al., 2022). Its productivity has lagged behind other industries, resulting in a $1.6 trillion value differential attributed to inefficiencies in project delivery and technology stagnation (Barbosa et al., 2017; Chen et al., 2021). According to statistics from 2015 to 2023, Malaysia's construction sector experienced a minimal decline in workforce numbers, in contrast to the more substantial workforce reduction observed in advanced nations (Statista, 2024a, 2024b). While advanced economies have turned to automation to offset labor shortages, Malaysia is still highly dependent on the labor workforce (Shang & Shen, 2018). The shift from the traditional construction technique to innovative approach is occurring slowly (Soon et al., 2024). Despite contributing 4% to 5% to national GDP, the value-added growth of construction sector has stagnated, with productivity metrics trailing other regions (Statista, 2024c). A low value of construction work underscores the insignificant contribution of the industry to the economy. Thus, it is crucial to implement innovative solutions like Unmanned Aerial Vehicles (UAVs) to improve the efficiency of the construction industry to produce a higher economic output. Skoda and Holcman (2021) point out that the utilization of UAVs is a crucial advancement in technology that will enhance the construction industry in terms of cost, quality, and time.

UAVs are an autonomous or remotely piloted aircraft with a payload for electronic devices (Albeaino & Gheisari, 2021). They can be equipped with cameras, communication devices, and light detection and ranging (LIDAR) equipment (Chonpatathip et al., 2023). Recent technological advancements have led to the development of more dependable, affordable, and controllable UAVs designs (Tatum & Liu, 2017b). This provides a wide range of UAVs-based functions for automation of the construction project development, including site surveying, project progress monitoring, infrastructure inspecting, material and machineries management, and physical building works (Elghaish et al., 2021). The data collected using UAVs can then be integrated with technologies such as Building Information Modeling (BIM) and Radio-Frequency Identification (RFID) to accomplish the task (Sanson, 2019). Globally, studies show that UAVs can reduce project timelines by 20% to 30% and lower inspection costs by 40% (Alsamarraie et al., 2022; Skoda & Holcman, 2021). However, UAVs adoption remains uneven, with developed nations leading in regulatory standardization and technical advancement, while developing economies like Malaysia face unique challenges such as tropical environmental constraints and underdeveloped policies (Soon et al., 2024).

While prior studies have explored UAVs applications and adoption challenges in the construction industry globally, there remains critical gaps. The existing research remains fragmented, lacking correlation analysis between adoption factors, and the insights from industry practitioners on mitigating these challenges are notably absent. This knowledge limitation significantly impedes the widespread adoption and strategic implementation of UAVs technologies. Thus, this study conducts a systematic literature review, synthesizing insights up to 80 academic studies to provide a comprehensive and contemporary examination of UAVs implementation opportunities in the construction industry. By offering a construction-specific analysis of UAVs use cases and developmental capabilities, the research presents unique and valuable contributions to the field. The primary objective of this investigation is to explore the opportunities UAVs can introduce to the construction sector. Moreover, the study critically assesses the multifaceted challenges surrounding UAVs integration, including organizational, regulatory, environmental, and technological barriers. Unlike prior studies that focus on isolated UAVs applications such as site surveying or inspections, our research integrates both opportunities and challenges into a unified conceptual framework by adopting the Technology-Organization-Environment (TOE) framework. TOE is widely used in examining organizational technology adoption as it represents not only the technological opportunities, but also the organizational readiness and environmental challenges (Baker, 2012). This framework bridges gaps between fragmented literature on UAVs productivity benefits and adoption barriers, offering a comprehensive view of UAVs implementation dynamics. Also, while existing research predominantly examines UAVs adoption in Western contexts, this study focuses on Malaysia's construction sector by enquiring from the local construction experts, extending the global discourse on UAVs adoption to understudied regions. The framework offers transferable insights that are relevant to other developing economies facing similar constraints. As a result, industry stakeholders can leverage these insights to navigate the evolving technological landscape, understanding how emerging technologies will enhance construction management practices.

2. Literature review

To establish a comprehensive foundation for this study, a detailed review of relevant literature was conducted. This review aims to synthesize existing knowledge on the application of UAVs in the construction industry, focusing on both the opportunities that UAVs present for improving productivity and the challenges that hinder their wider adoption. The extracted findings from the literature form the theoretical basis for identifying critical factors, which are subsequently validated through empirical research. The review is organized into two main sub-sections, which are opportunities of UAVs adoption and challenges of UAVs adoption in construction projects.

2.1. Opportunities and need for UAVs adoption

The construction sector in Malaysia faces growing pressure to improve project delivery efficiency, experiencing a significant increase in workforce participation within its labor market during the last ten years (Mydin et al., 2014). The construction sector has increasingly adopted UAVs technology over recent decades as a response to operational challenges, serving multiple functions, from gathering site information to conducting topographical surveys and various types of inspections (Motawa & Kardakou, 2018). According to Nassereddine (2022), UAVs could be used during any point in a project lifecycle, from its initial design stages to pre-planning, construction phase through management, operation, and asset management's final phases. The data collecting abilities of UAVs on construction sites make them more efficient, precise, and cost-effective than the traditional techniques (Elghaish et al., 2021). Despite significant awareness about potential benefits of UAVs in construction, current use remains low (Soon et al., 2024).

Wu et al. (2021) stated that UAVs with cameras for oblique photography could provide numerous perspectives that can be turned into three-dimensional models and wide views. This method is easier for site surveying by offering both physical description and visual appearance on one flight, hence allowing for all kinds of studies such as creating maps showing land relief and measuring volume of mountainsides (Chonpatathip, 2023). Therefore, UAVs photogrammetry is usually faster and more precise than conventional methods like satellites and manned vehicles (Reynoso-Vanderhorst et al., 2019). According to Hammad et al. (2021), UAVs with its small sizing can fly at different heights, enabling them to efficiently move through confined spaces, elaborate structures, and rough landscapes that human beings find difficult to enter. Additionally, the use of UAVs in surveying dangerous zones removes the requirement for installing heavy machinery and raising platforms that may be time-consuming and risky. As a result, they offer substantial flexibility and maneuverability which are useful for examining parts that are hard to reach (Nassereddine, 2022).

The use of UAVs in finishing works on walls and during plastering activities along the vertical rises is also practical as they can perform this task without employing humans (Nassereddine, 2022). UAVs have the capability to apply finishing materials accurately using modern technologies such as robotic arms, achieving consistent coverage with high-quality results. According to Chen et al. (2021), UAVs integrated with RFID technology can optimize coordination and collaboration among different trades on a construction site. This integration can provide real-time location and measurement tracking of materials and equipment on construction sites by allowing UAVs to scan RFID tags on them (Sanson, 2019). Locations and quantities of the items are updated and shared among multiple disciplines via a site management system. As a result, there will be less material shortage or equipment ordering delays.

Extracted factors of opportunities of UAVs adoption in the construction industry are summarized in Table 1.

Table 1. Extracted factors of opportunities of UAVs adoption in the construction industry

	Factors	Reference
	Site Surveying	
SS1	Time-efficient for geophysical surveys	Grigoriev et al. (2021)
SS2	High productivity in accessing landslide-prone areas	Soleimani et al. (2024)
SS3	Earthwork volumes determination for road construction	Chonpatathip et al. (2023)
SS4	Information linkage with simultaneous data measurement and interpretation	Ji et al. (2020)
SS5	Automated point-cloud acquisition process	Kim et al. (2019)
SS6	Enhancing site surveying via UAV photogrammetry	Chonpatathip (2023)
SS7	3D modeling and panoramic data from oblique photography	Wu et al. (2021)
SS8	UAV-BIM integrates the topography phase	Rizo-Maestre et al. (2020)
SS9	3D terrain models in determining rock volume	Matolák et al. (2019)
SS10	Time efficiency in urban planning and management	Trung et al. (2023)
SS11	Greater speed of high-resolution images	Reynoso-Vanderhorst et al. (2019)
	Site Inspection	
SI1	Flexibility and maneuverability in accessing hard-to-reach areas	Hammad et al. (2021)
SI2	Elimination of heavy equipment and elevating platforms	Nassereddine (2022)
SI3	Shorter inspection durations via e-inspection technologies	Mohamed and Tran (2023)
SI4	Detecting fault points in the transmission lines construction	Ni and Zhan (2022)
SI5	Identifying defects or mutual collisions between components	Wang (2023)
	Constructing and Repairing	
CR1	Multi-agent automated dry masonry construction	Elkhapery et al. (2023)
CR2	Post-construction maintenance and post-disaster reconnaissance	Albeaino and Gheisari (2021)
CR3	Finishing of walls and vertical slopes	Nassereddine (2022)
CR4	Lower percentage of non-contributory work	Castañeda et al. (2020)
CR5	Structure repairs in dangerous area	Elmousalami (2020), York et al. (2020)
CR6	Automated assembly of structure made from modular units	Tatum and Liu (2017a)
	Enhancing Manpower, Materials, and Machinery (3M) Coordination	
MM1	Generating multiple automated paths for construction rollers	Kim et al. (2023)
MM2	Real-time location and measurement tracking of materials	Sanson (2019)
MM3	Efficient levelling tasks using autonomous dozers	Dupont et al. (2017)
MM4	Optimizing coordination and collaboration among different trades	Chen et al. (2021)
MM5	3D modeling techniques in worker training	Keyvanfar and Shafaghat (2022)
MM6	Generating optimal crane lifting plans via 4D simulation	Tian et al. (2021)
MM7	Transporting construction materials on-site	Li and Liu (2019)

2.2. Challenges of UAVs adoption

Safety may be compromised by several factors arising from pilot errors or machine failure (Soon et al., 2024). UAVs operators who are inadequately trained can make mistakes including wrong course or deviating from safety protocols during flight. There may be mechanical failure in the equipment, while electronic malfunction could also happen unexpectedly making the UAVs crash or act in an unpredictable manner. These will result in accidents leading to injuries because of those errors. According to Mohamed and Tran (2023), significant economic challenges arise from the high capital and operational costs of UAVs utilization. To get high quality UAVs and related equipment, a high investment upfront is required. Continuous maintenance repair and parts replacements are operational expenses done on UAVs to prevent them from breaking down and keep them in their best operating condition.

According to Hammad et al. (2021), one of the significant environmental challenges is information clutter caused by vision obstructions from obstacles. Construction sites are usually filled with equipment, scaffoldings, and partly constructed buildings that might block the UAVs camera's sight. Moreover, bad weather and rugged terrains bring significant flying difficulties for UAVs in the construction sites (Nassereddine, 2022). Such challenges may result in false or incomplete information and hence, rendering the UAVs ineffectiveness. Use of UAVs in construction sites faces a big hurdle of inconsistency in operation regulations by the local governments (Alsamarraie et al., 2022). Every area has its own policies, such as permission during flights, safety precautions during operation, and data security law. According to Kim and Lee (2017), the capabilities and effectiveness of UAVs may be limited due to the high payload demand. UAVs tend to have shorter flight duration times due to their inadequate power supply and heavy mounting of equipment (Trung et al., 2023). Thus, extended downtime for recharging can disrupt project timelines and reduce overall efficiency.

Extracted factors of challenges of UAVs adoption in the construction industry are summarized in Table 2.

Table 2. Extracted factors of challenges of UAVs adoption in the construction industry

	Factors	Reference
	Safety Concerns	
SC1	Safety hazards in indoor operations	McCabe et al. (2017)
SC2	Lack of confidence due to immature technology	Soon et al. (2024)
SC3	Operator errors and equipment fatality	Soon et al. (2024)
SC4	Extending property damage risk to surrounding areas.	Tatum and Liu (2017b)
	Cost Challenges	
CC1	Additional resource allocation for UAV operators training	Alsamarraie et al. (2022)
CC2	High capital and operational costs	Mohamed and Tran (2023)
CC3	Additional cost in hiring certified UAV operators	Golizadeh et al. (2019)
	Environmental Factors	
EF1	Information clutters due to vision obstruction from obstacles	Hammad et al. (2021)
EF2	Terrain features of varying vegetation degrees	Sestras et al. (2023)
EF3	CO_2 emissions and noise pollution	Alsamarraie et al. (2022)
EF4	Severe weather and rugged terrains	Nassereddine (2022)
	Regulation Factors	
RF1	Application confined to specific project types	Albeaino and Gheisari (2021)
RF2	Security and privacy concerns from surrounding citizens	Nassereddine (2022)
RF3	Risk of data loss due to documentation failures	Golizadeh et al. (2019)
RF4	Lack of implementation of UAV regulations by local authorities	Alsamarraie et al. (2022)
RF5	Heightened liability and legal challenges	Albeaino and Gheisari (2021),
	Technical Difficulties	
TD1	Inaccurate result due to insufficient Ground Control Point (GCP)	Chonpatathip et al. (2023)
TD2	Limited flight duration due to insufficient battery capacity	Trung et al. (2023)
TD3	Interference to wireless technologies within an indoor environment	McCabe et al. (2017)
TD4	Straining of capabilities due to payload demand	Li and Liu (2019)
TD5	Inability to land autonomously in remote locations	York et al. (2020)

3. Methodology

A systematic approach was utilized to achieve the objectives of this study. The study began with defining the research problem by identifying gaps in implementing UAVs for construction productivity. A literature review was conducted to identify the current adaptation and application of UAVs in the construction industry. The factors of opportunities and challenges of UAVs adoption were extracted and further classified into thematic subgroups. The next phase of the study involved creating the semi-structured interview and questionnaire survey to obtain the construction stakeholders' viewpoints qualitatively and quantitatively, including the industry experts and academicians (see Appendix). The semi-structured interview was conducted to validate whether the factors gathered in global studies are relevant and prioritized in Malaysia's construction context. It also captures expert insights to address challenges in UAVs implementation. These validated factors were subsequently formed into structured survey items, ensuring that the questionnaire design reflected both theoretical constructs and industry perspectives. Qualitative analysis utilized description-focused coding using QDA Miner Lite, whereas quantitative analysis was conducted using Statistical Package Social Sciences (SPSS) with Analysis of Moment Structures (AMOS) extension, including three distinct stages, Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and Structural Modeling (SM). A conceptual framework was then generated to facilitate the adoption of UAVs in the construction industry, based on the Technology-Organization-Environment (TOE) framework and the Iron Triangle of Project Management. This framework categorization method provided a structured basis for developing the constructs of opportunities and challenges, ensuring that the following validation steps are based on an established adoption theory. The framework underwent validation process through expert feedback if any revision is required. The flowchart of the research to achieve the outcomes is as shown in Figure 1.

Combining qualitative and quantitative data, we addressed the limitations of prior single-method studies, such as the conceptual research conducted by Albeaino and Gheisari (2021). By validating constructs through EFA-CFA-SM, we can confirm the interdependencies between the factors of opportunities and challenges respectively, such as site surveying enabling 3M factors optimization and safety concerns amplifying cost barriers. Another example of the mixed-method design advantage is that the qualitative insights confirm why privacy concerns emerged as a critical regulatory barrier in Malaysia, while CFA-SM quantified its systemic impact.

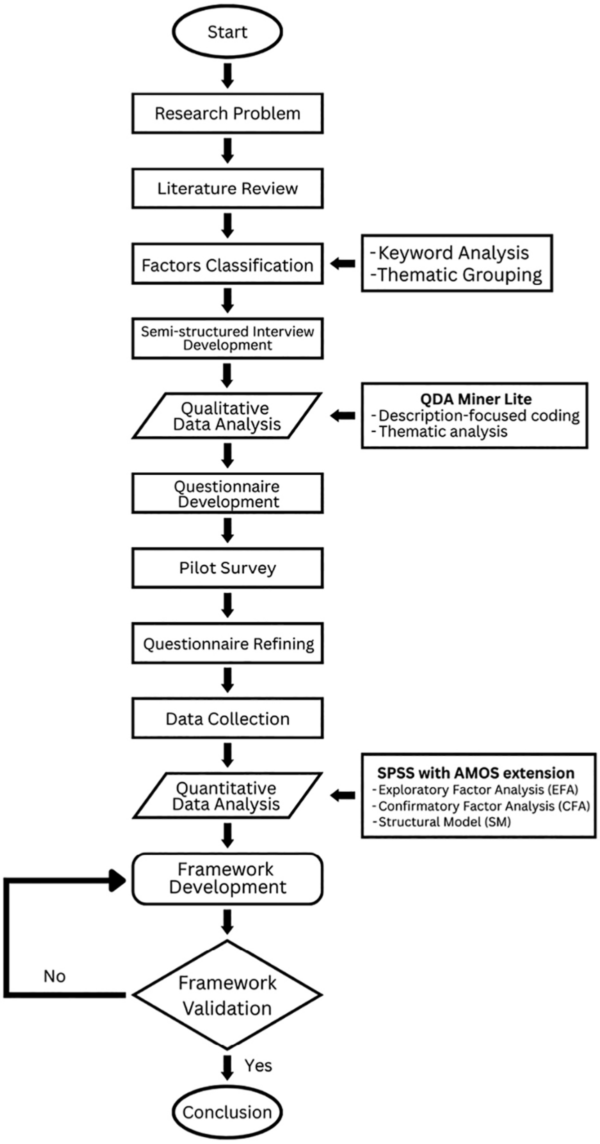

Figure 1. Flowchart of research methodology

3.1. Systematic review methodology

A strategy was developed to extract data from various databases to gather relevant literature according to the scope of the study. The Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA) was adopted to enhance the quality and clarity of reporting in systematic reviews and meta-analyzers according to a set of guidelines. It encompasses a 4-phase process as shown in Figure 2, starting with identification, screening, eligibility, and finally inclusion, to address the objectives of the study. The main objective of PRISMA statement is to improve the content transparency and integrity of the reporting in systematic reviews (Page et al., 2021). Hence, the readers can understand the rationale, methods, and results of the study more clearly.

Three databases were selected for this purpose: Scopus, Web of Science, and Google Scholar, as they are considered top databases that encompass all indexed articles. The data was searched within these databases using the search string ("Unmanned Aerial Vehicle" OR "UAV" AND "Construction" AND "Project"). The search was filtered to include English language articles published between 2014 and 2024 to ensure coverage of recent literature while connecting to past research. Additionally, document

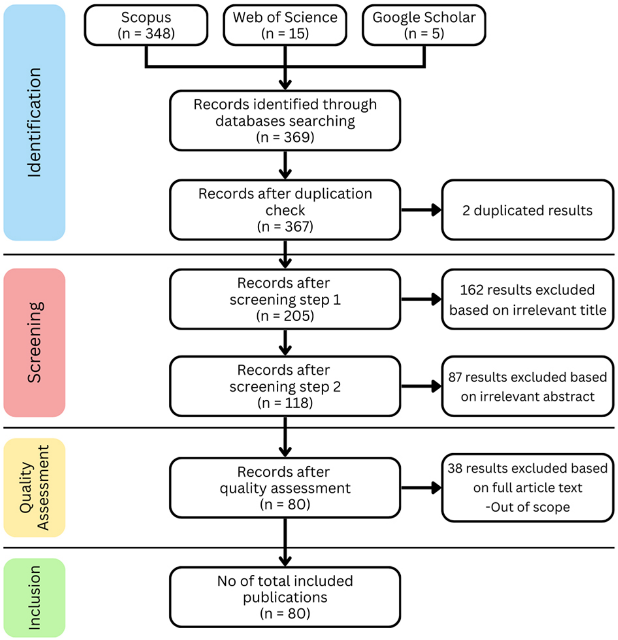

Figure 2. PRISMA statement in systematic review

type limitations were applied, focusing on research articles, review papers, and conference papers to gather only relevant publications. A total of 369 documents was identified after including the limitations mentioned above. The documents were then gone through several screening stages, which are the checking of duplication, irrelevant title, irrelevant abstract, and finally based on the scope of full article text. The retained studies were evaluated using a 5-point checklist adapted from Xiao and Watson (2017), which are the clarity of research objectives, methodological precision, contextual relevance, geographic focus, and stakeholder perspectives. As a result, 80 relevant publications were included for further studies.

After the literature collection and screening stage, the factors were extracted originally from the literature, and the redundant factors were merged. Thematic grouping approach was adopted to categorize the factors into subgroups. The subgroups for opportunities of UAVs adoption were created based on their alignment with the construction project phases, which are site surveying, site inspection, and constructing and repairing, followed by enhancing 3M coordination, which serve as the resources utilized throughout the project phases. This classification reflects how UAVs enhance productivity across the project lifecycle. The challenges of UAVs adoption were grouped into themes commonly used in the technology adoption framework. These categories align with the PESTEL framework (Political, Economic, Social, Technological, Environmental, Legal), adapted to the specific barriers of UAVs. The classification was refined by revisiting the literature to ensure keyword alignment and contextual relevance.

3.2. Semi-structured interview

The questions were organized within a prepared thematic structure to gather data through a semi-structured interview. This interview focused on the opportunities and challenges of UAVs adoption in the Malaysian construction industry, allowing for versatility and open-ended responses. The questions were categorized into sections, with respect to the factors extracted in the literature review. The study employed a purposive sampling technique, a widely used approach in qualitative research. Individuals were chosen based on their distinct traits or experiences directly relevant to the focus of the study, ensuring the collection of rich and varied perspectives (Rai & Thapa, 2015). The selection of construction personnel and lecturers as interviewees was based on several criteria. The industry experts have a minimum 10 years of working experience in the construction sector, whereas the lecturers with current part-time or prior industry experience of minimum 5 years are selected. They have a direct involvement in UAVs application on-site or workshops. The sample size estimation utilized rules of thumb recommended by qualitative research experts, based on methodological principles and experiential benchmarks (Sharma et al., 2024). 15 participants is the minimum acceptable number for all qualitative research (Sharma et al., 2024).

The qualitative data obtained was then analyzed using QDA Miner Lite, a qualitative data analysis software designed for systematic coding and thematic categorization (Adu, 2019). Thematic analysis, with the coding strategy of description-focused coding was adopted, which summarize and organize participants' responses into interpretable units while retaining contextual meaning. The interview transcripts were first broken down into different codes, which describe the main ideas from the participants. Codes with similar concepts were grouped into themes using QDA Miner Lite's hierarchical categorization tools. The software was selected due to its efficiency in processing large datasets with its automated search functions and code merging capabilities. It also provides visualization tools such as word cloud that align with the iterative pattern of thematic analysis.

3.3. Questionnaire survey

A questionnaire survey was developed to assess the improvement in workforce productivity through the adoption of UAVs and the challenges faced. A diverse range of construction stakeholders across Malaysia was targeted to ensure broad representativeness. Participants included various roles from contractors, consultants, clients, and academics, regardless of their years of experience, ranging from early-career to well-experienced personnel. This approach contrasts with the interviews, which focused on experts with deep UAVs-related experience, thereby balancing general insights with specialized depth. The first section is related to the general profile of the respondents. The second section acquires the awareness of the respondents on the adoption of UAVs on construction project. The third session is related to the impact of UAVs adoption on construction project productivity enhancement. The fourth section focuses on the challenges faced and the recommendations in facilitating the adoption of

UAVs in the construction industry. The third and fourth sections utilized a Likert scale with five response options, ranging from "Strongly Disagree" (scored as 1) to "Strongly Agree" (scored as 5), with "Disagree" (2), "Neutral" (3), and "Agree" (4) as the intermediate points. This approach is beneficial in presenting findings that are transparent and easy to comprehend. The questionnaire was distributed to participants in the construction industry, with most of them encompassing experience in operating UAVs.

Prior to full distribution, the questionnaire underwent a pilot survey with 12 industry experts to validate its reliability and content relevance (Bujang et al., 2024). They were drawn exclusively from the interview sample, based on their profound industry experience, direct UAVs involvement, and role diversity. By leveraging insights from the same experts interviewed earlier, the pilot survey ensured continuity between qualitative findings and quantitative instrument design. Based on their feedback, several improvements were implemented. The modifications included clarifying unclear questions and eliminating redundant items to create a more focused and concise survey instrument. SPSS with AMOS extension was then used to analyze the quantitative data obtained from the respondents. Cochran's formula was used to determine the sample size for the unknown population (Singh & Masuku, 2014).

$$\text{Sample size} = \frac{\left(Z.Score\right)^2 * StdDev * \left(1 - StdDev\right)}{\left(\text{Confidence interval}\right)^2}. \quad (1)$$

The confidence level of the questionnaire survey is related to the "Z-score", or standard score. The percentage of the confidence level corresponds to the number of standard deviations above or below the population mean, as indicated by the associated Z-score value. To determine the appropriate sample size for the questionnaire survey, statistical parameters were selected based on the variability in responses from the target population. A standard deviation of 0.5 was used, with a z-score of 1.65 for a 90% confidence level. A standard margin of error of 6% was applied as the confidence interval. As a result, the sample size computed was 189 respondents.

3.3.1. Exploratory Factor Analysis (EFA)

EFA is a multivariate statistical technique that uncovers the most concise set of underlying constructs or factors that can effectively account for the observed patterns of covariation among a group of measured variables. In essence, EFA seeks to reveal the fundamental factors that elucidate the inherent structure and relationships within a set of observed measurements (Watkins, 2018). The process of EFA typically unfolds in three critical phases, which are data suitability assessment, factors extraction, and factors rotation and interpretation (Dragan & Topolšek, 2014).

The initial phase, data suitability assessment, assesses whether the data is appropriate for factor analysis. It involves examining the sample size and the strength of variable correlations. According to Dragan and Topolšek (2014), while opinions vary, researchers generally recommend a sample size between 150 to 300 cases. In this study, data from 200 respondents was collected, meeting this criterion. The analysis also involves checking the correlation matrix for coefficients exceeding 0.3, indicating sufficient inter-variable relationships (Dragan & Topolšek, 2014). To confirm these conditions, the Kaiser-Meyer-Olkin (KMO) sampling adequacy measure and Bartlett's sphericity test are typically employed (Watkins, 2018).

The second stage, which is factors extraction, aims to determine the smallest number of factors that can adequately represent the relationships among variables. Various extraction methods can be chosen, including principal component analysis, principal factors, image factoring, and generalized least squares. Principal component analysis is a commonly used technique. The number of factors to retain is often decided using methods such as Kaiser's criterion, scree test, or parallel analysis (Dragan & Topolšek, 2014; Watkins, 2018). For this study, Kaiser's criterion was applied.

The final stage, which is factors rotation and interpretation, involves rotating the extracted factors to improve their interpretability without altering the underlying solution. This process helps present the components as clusters of variables. Common rotation techniques include varimax, quartimax, and equamax (Dragan & Topolšek, 2014; Watkins, 2018). In this study, the varimax rotation method was utilized to enhance factor clarity and facilitate interpretation.

The appropriateness of factor analysis is often determined by examining the KMO measure. Generally, a KMO value above 0.5 is considered acceptable, but values of 0.8 or higher are preferred for robust analysis (Dragan & Topolšek, 2014). Some researchers suggest a more stringent cutoff, recommending a KMO of at least 0.70 for optimal results (Bernard et al., 2020; Dragan & Topolšek, 2014; Watkins, 2018). In addition to the KMO, Bartlett's test of sphericity is used to assess the suitability of the factor model. A significance level below 0.05 in Bartlett's test indicates that there are likely meaningful correlations among the variables in the dataset (Arokodare & Asikhia, 2020). This suggests that the data can be reasonably grouped into factors or clusters.

3.3.2. Structural Equation Modeling (SEM)

SEM is a flexible statistical approach used to analyze complex relationships among multiple variables. This technique is driven by hypotheses and employs a structural model to represent proposed connections between various factors, allowing researchers to test and visualize how different variables interact and influence each other within a system (Stephan et al., 2009). A minimum sample size of 200 is often required for SEM when the model complexity is moderate, which is regarded as a large sample approach (Dash & Paul, 2021). SEM is composed of two models, which are the measurement model and structural model. The formal performs CFA, which is a statistical method employed to evaluate the effectiveness of hypothesized model structures to fit the actual data, providing insights into the validity of theoretical constructs and their measurable indicators (Price, 2023). The latter consists of a series of hypothesized relationships that describes the interactions between latent variables and directly observable variables (Bhale & Bedi, 2024). Essentially, the structural model provides a comprehensive framework for understanding the complex network of relationships among various constructs within the study. The two-step approach follows SEM conventions that promote measurement accuracy and result credibility (Jusoh et al., 2021). By first confirming constructs through CFA, the structural relationships in SM are not influenced by poorly defined variables. CFA forms the distinctness between constructs and SM reveals the interaction between validated constructs.

To assess the reliability and validity of the model, a measurement model for CFA was developed using the collected data. In CFA, a factor loading of 0.7 is typically considered sufficient for contributing to the latent variable (Brown, 2015). Items with factor loadings below this threshold are generally eliminated from the CFA model. Following the successful validation of the measurement model, a structural model was developed and evaluated for both opportunities and challenges of UAVs adoption in the construction industry respectively. These models' fit was assessed using goodness of fit (GOF) indices to verify its adequacy in representing the hypothesized relationships.

4. Results and discussion

According to the responses obtained from the semi-structured interviews and distribution of questionnaires, a mixed approach of qualitative and quantitative analysis was conducted to investigate the findings of this study.

4.1. Qualitative research outcomes

A total of 20 participants' responses, ranging from the age of 36 to 53 years old, were collected in the semi-structured interview, including various designations from the organizations of contractors, consultants, and academia. In terms of their gender, male respondents (*n* = 16.80%) are dominant over the female respondents. Most of them hold a bachelor's degree (*n* = 13.65%), followed by a master's degree (*n* = 6.35%), and finally only 1 respondent who holds a PhD Degree. Almost half of them have had more than 15 years of working experience (*n* = 9.45%).

The semi-structured interview started by enquiring with the participants on their general understanding of the adoption rate and the role of UAVs in enhancing the productivity of the construction industry. Their opinions on the opportunities and challenges of UAVs adoption in the construction industry were then acquired accordingly. Table 3 illustrates the frequency of themes, where the codes count represents the total number of interviewees' main ideas that are further grouped into distinct themes through thematic analysis, and the cases count represents the total number of participants stating the respective idea. The result is then tabulated by QDA Miner Lite's analysis tools. A higher frequency of codes count indicates a higher significance of the themes. Figure 3 shows the word cloud of the themes extracted, a visual presentation of the significancy of the themes.

Based on the evaluation of semi-structured interview, there are some recommendations to cope with the barriers and foster the development of UAVs. The successful implementation of UAVs technology in construction relies on five critical factors. Safety management focuses on establishing robust protocols for indoor operations, ensuring proper operator certification, and implementing comprehensive equipment safety measures to minimize risks. Moreover, technical solutions address the improvement of resistance to enhancement of battery efficiency for extended operation times, and development of autonomous capabilities for improved performance. Furthermore, the government should provide essential guidelines from local authorities, measures for protecting privacy of surrounding areas, and standardized documentation procedures to ensure compliance in the regulatory framework. Financial support mechanisms including government incentives and subsidies can be introduced to reduce initial investment barriers. Cost optimization such as industry-academia partnership funding to promote research and development, and tax benefits to encourage technology adoption can be explored. Lastly, environmental considerations should account for weather-related challenges through adaptation strategies, enhancement of vision systems for better performance in various conditions, and control of emissions to maintain environmental sustainability. Successful UAVs implementation in construction depends on coordinated efforts among multiple stakeholders, including regulatory bodies, project managers, and UAVs operators.

4.2. Quantitative research outcomes

The proper sample size was determined using a well-established random sampling technique to guarantee adequate representation of the research population. Using Eqn (1), 189 responses is the minimal sample size needed for the target population. To ensure a comprehensive data collection, more than 400 questionnaires were disseminated, with a specific focus on professionals from Malaysian academic fields, contractors, consultants, and clients. To ensure that every individual had an equal chance of being included in the survey, random sampling was used to select participants from the target population for this vast distribution. By using this method, the sample is more representative, and the results are more broadly applicable.

The total number of responses obtained was 200, where data analysis was conducted using the SPSS-AMOS software. The results of the survey were organized into distinct categories as follows:

1. Demographic profile of the respondents.
2. Awareness of respondents on the application of UAVs in the construction industry.
3. Opportunities of UAVs adoption in enhancing productivity in the construction industry.
4. Challenges faced in UAVs adoption in the construction sector.

Table 3. Frequency of themes extracted through thematic analysis

Themes	Codes Count	Codes Percentage (%)	Cases Count	Cases Percentage (%)
Section 1: General Understanding of Application of UAVs				
Site safety	7	0.7	5	25.0
High efficiency	16	1.5	12	60.0
High accuracy of results	19	1.8	16	80.0
Improving different project phases	8	0.8	7	35.0
Limited adoption in smaller firm	12	1.2	12	60.0
Wide adoption in large scale project	28	2.7	19	95.0
Section 2: Opportunities of UAVs Adoption (Site Surveying)				
High efficiency and accuracy	64	6.2	20	100.0
Avoiding project rework and delay	46	4.4	19	95.0
Promoting site safety	8	0.8	4	20.0
Section 3: Opportunities of UAVs Adoption (Site Inspection)				
High efficiency of site inspection	27	2.6	19	95.0
Ensuring workplace safety	14	1.3	10	50.0
Ensuring work compliance	37	3.6	20	100.0
Limitation of internal inspection	1	0.1	1	5.0
Section 4: Opportunities of UAVs Adoption (Constructing and Repairing)				
High precision in simple tasks	37	3.6	19	95.0
Limited capabilities in complex automated tasks	21	2.0	16	80.0
Post construction applications	26	2.5	18	90.0
Section 5: Opportunities of UAVs Adoption (Enhancing 3M Coordination)				
Ensuring availability of materials on site	38	3.7	20	100.0
Assisting in workers' training programs	35	3.4	20	100.0
Enhancing coordination of machinery and equipment	20	1.9	20	100.0
Section 6: Challenges of UAVs Adoption (Safety Concerns)				
Risk of injury to workers and damage to properties	42	4.0	20	100.0
Immature of technology and regulations	11	1.1	11	55.0
Mature technology and regulations	9	0.9	9	45.0
Training program for operators and workers	8	0.8	7	35.0
Continuous improvements on UAVs	16	1.5	15	75.0
Generating UAVs operation guidelines	30	2.9	19	95.0
Section 7: Challenges of UAVs Adoption (Cost Challenges)				
High life cycle cost	39	3.8	20	100.0
High return on investment	41	3.9	20	100.0
Seeking of financial aid	5	0.5	5	25.0
Renting or partnership	14	1.3	13	65.0
Partly adoption of UAVs	12	1.2	12	60.0
Section 8: Challenges of UAVs Adoption (Environmental Factors)				
Sensitive to environmental changes	40	3.8	20	100.0
Low emissions	21	2.0	20	100.0
Establishing guidelines and regulations	10	1.0	10	50.0
Noise impact on surrounding people	17	1.6	17	85.0
Establishing an operation plan with minimal impact	20	1.9	17	85.0
Investing in environmentally friendly model	26	2.5	20	100.0
Section 9: Challenges of UAVs Adoption (Regulation Factors)				
Regulation challenges	60	5.8	20	100.0
Developing clear regulatory framework	33	3.2	20	100.0
Close communication among the stakeholders	4	0.4	4	20.0
Section 10: Challenges of UAVs Adoption (Technical Difficulties)				
External causes of technical difficulties	10	1.0	10	50.0
Internal causes of technical difficulties	64	6.2	20	100.0
Improving UAVs equipment	15	1.4	13	65.0
Enhancing indoor applications of UAVs	1	0.1	1	5.0
Integrating new features	28	2.7	19	95.0

Figure 3. Word cloud of the extracted themes

4.2.1. Demographic profile of the respondents

The demographic profile of the respondents of the questionnaire survey is shown in Figure 4. Overall, most of the respondents hold a bachelor's degree, with a percentage of 70.5%. They come mainly from the contractors (53.5%), followed by the consultants (43%). The working experience of the respondents is almost equally distributed. There are various designations, where the option of "others" includes quantity surveyor, safety engineer, site foreman, BIM engineer, etc.

4.2.2. Awareness level of UAVs implementation

The level of awareness of respondents on the implementation of UAVs in the construction industry was examined, showing that most of them only hear about UAVs but are not fully familiar with their potential benefits (64%). Almost half of the respondents have never had any experience of UAVs training (45.4%), followed by 29% of the respondents rarely had any UAVs training before. A significant majority of respondents, over 84%, reported having relatively limited experience with UAVs implementation, ranging from no experience at all to a maximum of 5 years. This data underscores the emerging nature of UAVs adoption within the construction industry.

4.2.3. EFA of opportunities of UAVs adoption

Starting with EFA on the first section, "Opportunities of UAVs Adoption", the initial KMO value obtained is 0.857 > 0.8, while the Bartlett's test of sphericity obtained is 3269.352 with a significance of 0.000 < 0.05. When pre-

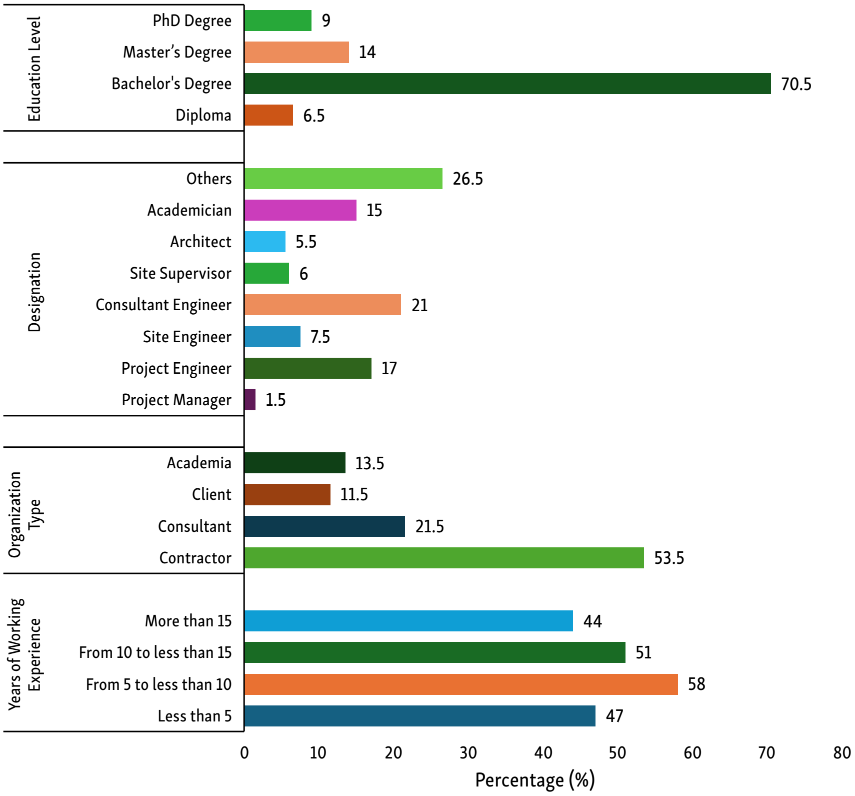

Figure 4. Demographic profile of the questionnaire respondents

paring for principal component analysis, the communalities extracted for each variable were evaluated. For results and interpretations to be considered reliable, it is generally recommended that the average communality exceeds 0.60 (Watkins, 2018). Additionally, according to a commonly accepted guideline, a variable should have an extraction value surpassing 0.50 in the initial iteration to be deemed potentially significant for the analysis (Watkins, 2018). Accordingly, there were two variables (SS6, MM6) identified with communalities values lower than 0.5 and hence, extracted for further analysis. The newly modified EFA has a new KMO and Bartlett's test of sphericity values of 0.861 and 2977.066 with a significance of 0.000 as shown in Table 4.

The analysis revealed four distinct factor components, as presented in Table 5. These components collectively account for 66.786% of the total variance in the data. This cumulative explained variance surpasses the generally accepted threshold of 50%, indicating a robust factor solution (Dragan & Topolšek, 2014; Watkins, 2018).

Furthermore, Table 6 presents the rotated component matrix, which demonstrates the emergence of four clearly differentiated components. Each variable exhibited a strong association with a single factor, allowing for a clear categorization. These distinct factors were identified as "Site Surveying" (SS), "Site Inspection" (SI), "Constructing and Repairing" (CR), and "Enhancing 3M Coordination" (MM).

Table 4. KMO and Bartlett's test of opportunities of UAVs adoption

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.861
Bartlett's Test of Sphericity	Approx. Chi-Square	2977.066
	df	351
	Sig.	0.000

Table 5. Total variance explained of opportunities of UAVs adoption

Total variance explained									
	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	12.854	44.324	44.324	12.854	44.324	44.324	12.854	44.324	44.324
2	2.818	9.717	54.041	2.818	9.717	54.041	2.818	9.717	54.041
3	2.056	7.090	61.131	2.056	7.090	61.131	2.056	7.090	61.131
4	1.64	5.655	66.786	1.64	5.655	66.786	1.64	5.655	66.786
5	0.895	3.086	69.872	–	–	–	–	–	–
6	0.799	2.755	72.628	–	–	–	–	–	–
7	0.756	2.607	75.234	–	–	–	–	–	–
8	0.69	2.379	77.614	–	–	–	–	–	–
9	0.659	2.272	79.886	–	–	–	–	–	–
10	0.53	1.828	81.714	–	–	–	–	–	–
11	0.52	1.793	83.507	–	–	–	–	–	–
12	0.472	1.628	85.134	–	–	–	–	–	–
13	0.449	1.548	86.683	–	–	–	–	–	–
14	0.43	1.483	88.166	–	–	–	–	–	–
15	0.425	1.466	89.631	–	–	–	–	–	–
16	0.407	1.403	91.034	–	–	–	–	–	–
17	0.355	1.224	92.259	–	–	–	–	–	–
18	0.321	1.107	93.366	–	–	–	–	–	–
19	0.295	1.017	94.383	–	–	–	–	–	–
20	0.289	0.997	95.379	–	–	–	–	–	–
21	0.276	0.952	96.331	–	–	–	–	–	–
22	0.214	0.738	97.069	–	–	–	–	–	–
23	0.206	0.710	97.779	–	–	–	–	–	–
24	0.204	0.703	98.483	–	–	–	–	–	–
25	0.166	0.572	99.055	–	–	–	–	–	–
26	0.145	0.500	99.555	–	–	–	–	–	–
27	0.129	0.445	100.000	–	–	–	–	–	–
Extraction Method: Principal Component Analysis									

Table 6. Rotated component matrix of opportunities of UAVs adoption

Rotated Component Matrix[a]				
	Component			
	1	2	3	4
Site Surveying				
SS1	0.540	–	–	–
SS2	0.615	–	–	–
SS3	0.773	–	–	–
SS4	0.584	–	–	–
SS5	0.614	–	–	–
SS7	0.697	–	–	–
SS8	0.680	–	–	–
SS9	0.601	–	–	0.565
SS10	0.622	–	–	–
SS11	0.711	–	–	–
Site Inspection				
SI1	–	0.704	–	–
SI2	–	0.625	–	–
SI3	–	0.612	–	–
SI4	–	0.714	–	–
SI5	–	0.689	–	–
Constructing and repairing				
CR1	–	–	0.612	–
CR2	–	–	0.556	–
CR3	0.551	–	0.561	–
CR4	–	–	0.629	–
CR5	–	–	0.669	–
CR6	–	–	0.585	–
Enhancing 3M Coordination				
MM1	–	–	–	0.702
MM2	–	–	–	0.549
MM3	–	–	–	0.596
MM4	–	–	–	0.598
MM5	–	–	–	0.789
MM7	–	–	–	0.610
Extraction Method: Principal Component Analysis Rotation Method: Varimax with Kaiser Normalization				

Note: a – Rotation converged in 8 iterations.

4.2.4. EFA of challenges of UAVs adoption

Moving on to the next section, "Challenges of UAVs adoption", the initial KMO value is 0.872 > 0.8, while the Bartlett's test of sphericity obtained is 2067.008 with a significance of 0.001. According to the communalities value generated for each variable, there was one variable (RF1) found with communalities values lower than 0.5 and hence, extracted for further analysis. Then, EFA now has a new KMO and Bartlett's test of sphericity values of 0.871 and 2074.787 with a significance of <.001 as shown in Table 7.

The analysis identified five distinct factor components, as tabulated in Table 8. These components collectively account for 65.645% of the total variance in the data, which exceeds the generally accepted threshold of 50%. Table 9 also explains the rotated component matrix, which shows the emergence of five differentiated components. They are "Safety Concerns" (SC), "Cost Challenges" (CC), "Environmental Factors" (EF), "Regulation factors" (RF), and "Technical Difficulties" (TD).

Table 7. KMO and Barlett's test of challenges of UAVs adoption

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.882
Bartlett's Test of Sphericity	Approx. Chi-Square	1914.631
	df	190
	Sig.	<0.001

4.2.5. CFA of opportunities of UAVs adoption

The research methodology employed a threshold for factor loadings, with variables scoring below 0.7 being excluded to refine the measurement model. In the section of "Opportunities of UAVs adoption", the EFA initially yielded 27 variables. However, one variable (MM5) from the "Enhancing 3M Coordination" (MM) category was removed from the final model due to its factor loading falling short of the 0.7 criterion, as illustrated in Figure 5.

The reliability and validity of the measurement model were evaluated to determine the model fit. Reliability measures how consistently the model measures the intended latent constructs, with construct reliability (CR) serving as the primary evaluation metric. Validity assessment focuses on ensuring the model accurately measures its intended constructs, using convergent validity (Average Variance Extracted – AVE) and GOF indices as key evaluation criteria (Swarni et al., 2024).

Based on the results of CR and AVE obtained in Table 10, the analysis revealed that the measurement model of "Opportunities of UAVs Adoption", satisfied both reliability and validity requirements. The model's overall fit was then evaluated using multiple GOF indicators as shown in Table 11, a crucial step in SEM. The CFA model demonstrated satisfactory GOF metrics when compared to established threshold values, enhancing the model's credibility (Swarni et al., 2024).

4.2.6. Challenges of UAVs adoption (CFA)

Figure 6 illustrates the CFA model of "Challenges of UAVs adoption", having total of 20 variables extracted from the previous EFA stage. All 20 observed variables have a factor loading equal or greater than 0.7, exceeding the threshold for acceptable construct validity. Hence, no variable was removed from the model. Considering the significance of the factor subgroups, "Safety Concerns" (0.42), "Cost Challenges" (0.44), and "Technical Difficulties" (0.45) have the strongest loadings. This result indicates that the challenges to UAVs adoption are multidimensional, with safety, cost, and technical issues being the most crucial challenges from stakeholder's viewpoint. Policymakers and construction firms should prioritize addressing these issues, such as clarifying regulatory frameworks (RF2-RF5) to mitigate adoption hesitancy.

Table 8. Total variance explained of challenges of UAVs adoption

Total Variance Explained									
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	7.544	37.720	37.720	7.544	37.720	37.720	4.135	20.675	20.675
2	2.337	11.686	49.407	2.337	11.686	49.407	3.750	18.752	39.427
3	1.158	5.789	55.195	1.158	5.789	55.195	2.254	11.268	50.695
4	1.080	5.400	60.595	1.080	5.400	60.595	1.980	9.901	60.595
5	1.010	5.050	65.645	1.010	5.050	65.645	1.010	5.050	65.645
6	0.868	4.338	69.983	–	–	–	–	–	–
7	0.792	3.960	73.943	–	–	–	–	–	–
8	0.680	3.398	77.341	–	–	–	–	–	–
9	0.645	3.226	80.567	–	–	–	–	–	–
10	0.534	2.668	83.235	–	–	–	–	–	–
11	0.514	2.569	85.803	–	–	–	–	–	–
12	0.438	2.190	87.993	–	–	–	–	–	–
13	0.392	1.960	89.953	–	–	–	–	–	–
14	0.369	1.847	91.800	–	–	–	–	–	–
15	0.356	1.782	93.582	–	–	–	–	–	–
16	0.319	1.594	95.177	–	–	–	–	–	–
17	0.289	1.445	96.622	–	–	–	–	–	–
18	0.241	1.207	97.829	–	–	–	–	–	–
19	0.225	1.125	98.955	–	–	–	–	–	–
20	0.209	1.045	100.000	–	–	–	–	–	–
Extraction Method: Principal Component Analysis									

Table 9. Rotated component matrix of challenges of UAVs adoption

Rotated Component Matrix[a]					
	Component				
	1	2	3	4	5
Safety Concerns					
SC1	0.569	–	–	–	–
SC2	0.731	–	–	–	–
SC3	0.779	–	–	–	–
SC4	0.741	–	–	–	–
Cost Challenges					
CC1	–	0.562	–	–	–
CC2	–	0.607	–	–	–
CC3	–	0.578	–	–	–
Environmental Factors					
EF1	–	–	0.607	–	–
EF2	–	–	0.582	–	–
EF3	–	–	0.765	–	–
EF4	–	–	0.682	–	–
Regulation Factors					
RF2	–	–	–	0.589	–
RF3	–	–	–	0.509	–
RF4	–	–	–	0.666	–
RF5	–	–	–	0.666	–
Technical Difficulties					
TD1	–	–	–	–	0.661
TD2	–	–	–	–	0.676
TD3	–	–	–	–	0.627
TD4	–	–	–	–	0.610
TD5	–	–	–	–	0.730
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.					

Note: a – Rotation converged in 9 iterations.

Table 12 shows the analysis outcomes of reliability and validity test of the measurement model "Challenges of UAVs Adoption", where both requirements were satisfied. The model's overall fit was then evaluated using multiple GOF indicators as shown in Table 13, where the GOF metrics were all satisfied.

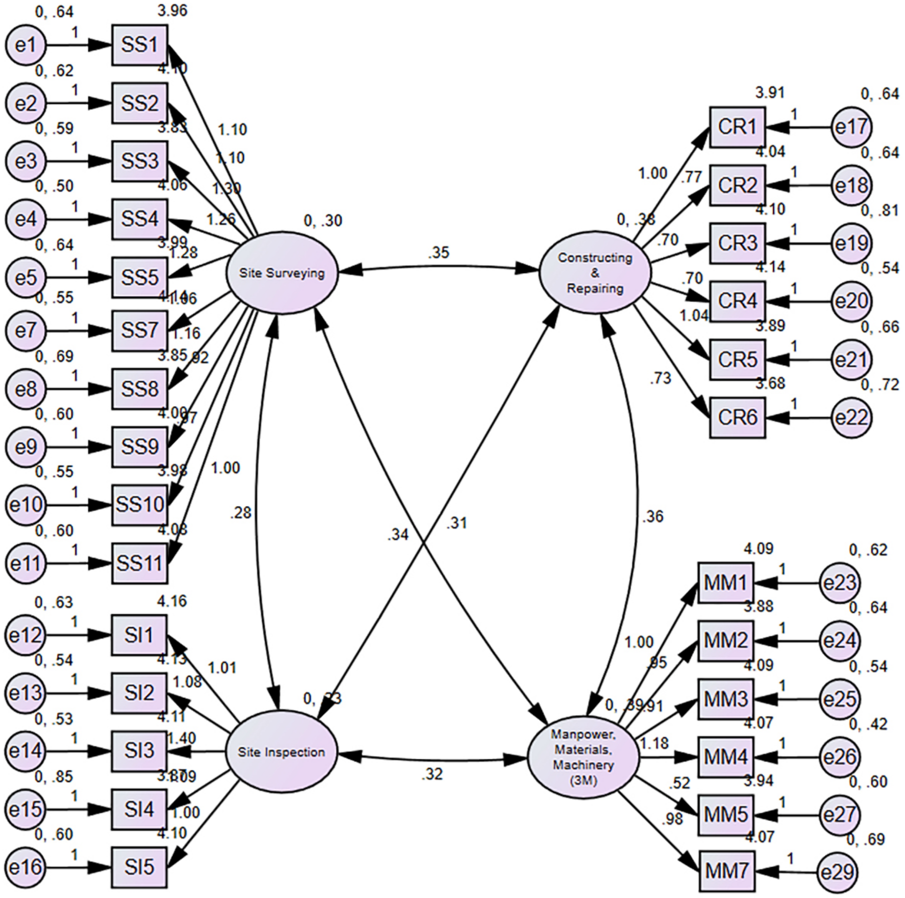

Figure 5. CFA model of opportunities of UAVs adoption

Table 10. Reliability and validity test of opportunities of UAVs adoption

Constructs	AVE > 0.5	CR > 0.6
Site Surveying	0.55	0.862
Site Inspection	0.60	0.700
Constructing and Repairing	0.51	0.696
Enhancing 3M Coordination	0.52	0.771

Table 11. GOF indices of the CFA model of opportunities of UAVs adoption

Category	Index Name	Index	Attained Values	Acceptance Criteria
Absolute Fit Indices	Discrepancy Chi square	Chisq	28.4	p > 0.01
	Goodness of Fit Index	GFI	0.926	>0.90
	Root Mean Square of Error Approximation	RMSEA	0.074	<0.08
Incremental Fit	Comparative Fit Index	CFI	0.947	>0.90
Indices	Tucker-Lewis Index	TLI	0.953	>0.90
Parsimonious Fit	Chi Square/Degree of freedom	Chisq/df	2.19	<3

Table 12. Reliability and validity test of challenges of UAVs adoption

Constructs	AVE > 0.5	CR > 0.6
Safety Concerns	0.56	0.680
Cost Challenges	0.545	0.622
Environmental Factors	0.52	0.663
Regulation Factors	0.59	0.611
Technical Difficulties	0.57	0.770

Table 13. GOF indices of the CFA model of challenges of UAVs adoption

Category	Index Name	Index	Attained Values	Acceptance Criteria
Absolute Fit Indices	Discrepancy Chi square	Chisq	32.1	p > 0.01
	Goodness of Fit Index	GFI	0.948	>0.90
	Root Mean Square of Error Approximation	RMSEA	0.073	<0.08
Incremental Fit	Comparative Fit Index	CFI	0.965	>0.90
Indices	Tucker-Lewis Index	TLI	0.961	>0.90
Parsimonious Fit	Chi Square/Degree of freedom	Chisq/df	2.37	<3

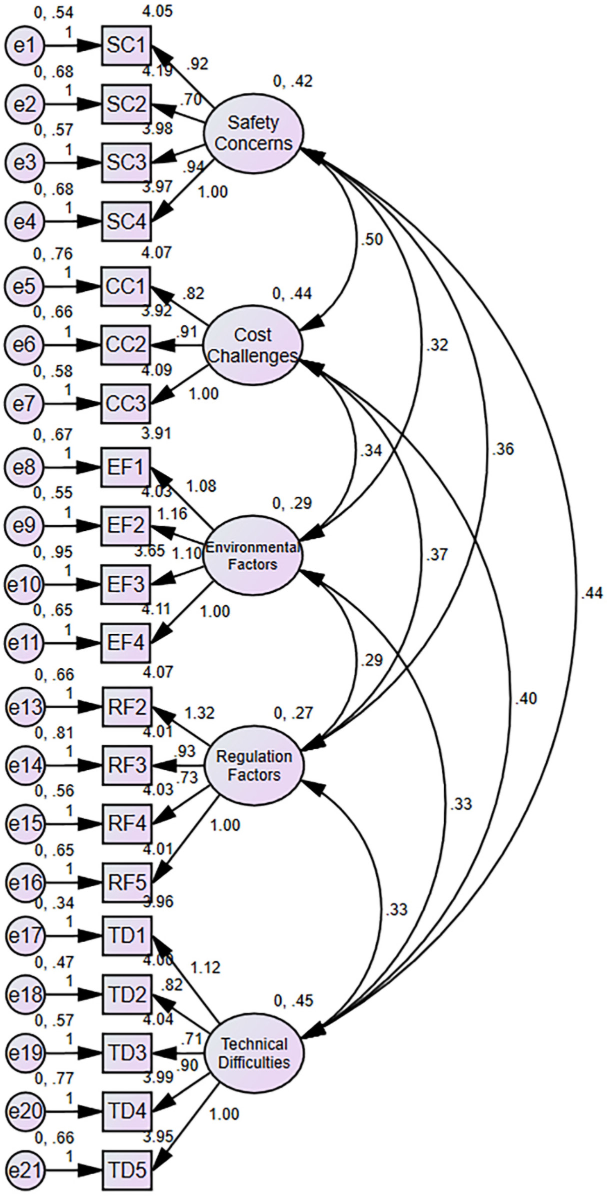

Figure 6. CFA model of challenges of UAVs adoption

4.2.7. SM of opportunities of UAVs adoption

The structural model examining opportunities for UAVs implementation in the construction industry as shown in Figure 7 demonstrated adequate model fit. Analysis of the GOF indices stated in Table 14 confirmed that the model sufficiently represents the data. The structural model highlights identified 4 primary constructs encompassing 27 factors that represent UAVs implementation opportunities for enhancing constructing productivity, which are “Site Surveying”, “Site Inspection”, “Constructing and Repairing”, “Enhancing 3M Coordination”. The analysis revealed statistically significant factor loading across all 27 factors, with values ranging from 0.51 to 1.38. Among the 4 constructs, “Constructing and Repairing” (0.62) showed the strongest influence on UAVs implementation in construction, followed by “Enhancing 3M Coordination” (0.61), “Site Surveying” (0.56), and “Site Inspection” (0.50).

Also, the model shows that the “Eliminating human labor for structure repairs in dangerous area” (CR5) with factor loading (1.03) has the highest impact among other factors within the category of “Constructing and Repairing”; “Optimizing coordination and collaboration among different trades” (MM4) with (1.16) has the highest impact within the “Enhancing 3M Coordination” category; “Determining earthwork volumes” (SS3) has the highest impact within the “Site Surveying” category, and “Shorter inspection durations” (SI3) has the highest impact within the “Site Inspection” category.

Table 15 presents a comprehensive overview of the factors of opportunities that were retained and eliminated during the development of the SEM.

4.2.8. Challenges of UAVs adoption (SM)

The structural model depicted in Figure 8, which addresses the challenges of UAVs implementation in the construction industry, demonstrated a good fit. The analysis of the GOF indices presented in Table 16 confirmed that the model adequately represents the data. The structural model highlights identified 5 primary constructs encompassing 20 factors that represent challenges of UAVs implementation in the construction industry, which are “Safety Concerns”, “Cost Challenges”, “Environmental Factors”, “Regulation Factors”, and “Technical Difficulties”. The analysis revealed statistically significant factor loadings across all 20 factors, with values ranging from 0.70 to 1.34. Among the 5 constructs, “Safety Concerns” (0.74) showed the strongest influence on UAVs implementation, followed by “Cost Challenges” (0.69), “Technical Difficulties” (0.61), “Regulation Factors” (0.53), and “Environmental Factors” (0.47).

Also, the model shows that the “Extending of property damage risk to surrounding areas” (SC4) with factor loading (1.00) has the highest impact among other factors within the category of “Safety Concerns”. This aligns with findings by Tatum and Liu (2017b), who identified that UAVs operations in highly populated areas is a critical liability concern, particularly in urban construction projects.

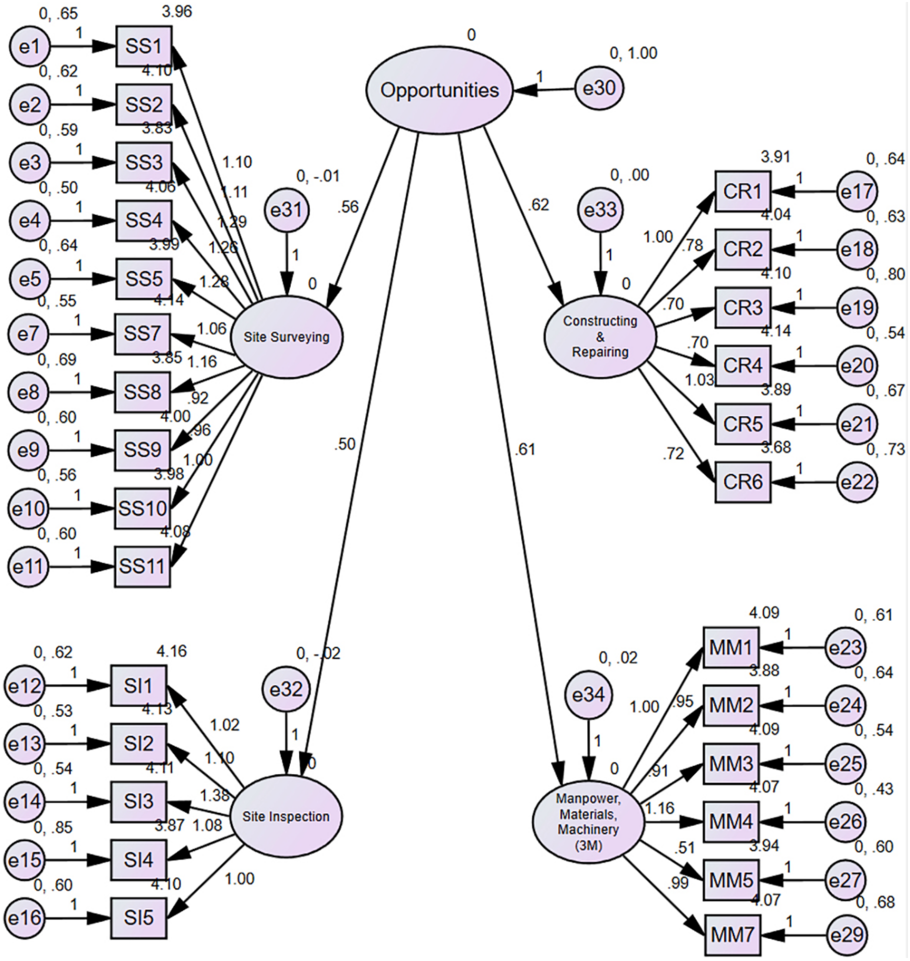

Figure 7. SM model of opportunities of UAVs adoption

Table 14. GOF indices of the SM model of opportunities of UAVs adoption

Category	Index Name	Index	Attained Values	Acceptance Criteria
Absolute Fit Indices	Discrepancy Chi square	Chisq	72.65	p > 0.01
	Goodness of Fit Index	GFI	0.931	>0.90
	Root Mean Square of Error Approximation	RMSEA	0.077	<0.08
Incremental Fit	Comparative Fit Index	CFI	0.952	>0.90
Indices	Tucker-Lewis Index	TLI	0.932	>0.90
Parsimonious Fit	Chi Square/Degree of freedom	Chisq/df	2.677	<3

“Additional cost in hiring certified UAVs operators” (CC3) with (1.00) has the highest impact within the “Cost Challenges” category. Similar challenges were reported by Golizadeh et al. (2019) that certification requirements inflate operational costs, especially for small construction firms. “Inaccurate result due to insufficient Ground Control Point (GCP) ” (TD1) with factor loading (1.13) has the highest impact within the “Technical Difficulties” category, supporting Chonpatathip et al. (2023), who stated that inadequate GCPs will reduce UAV photogrammetry accuracy in terrain modeling. “Security and privacy concerns from surrounding citizens” (RF2) has the highest impact within the “Regulation Factors” category. This aligns with Nassereddine (2022), who demonstrated that privacy violations is a key barrier to UAV adoption, particularly in urban areas where drones unintentionally capture data on adjacent properties or individuals. Lastly, “Terrain features of varying vegetation degrees” (EF2) with factor loading (1.26) has the highest impact within the “Environmental Factors” category. Sestras et al. (2023) found that dense vegetation complicates the navigation and data reliability of UAVs.

Table 17 presents a comprehensive overview of the factors of challenges that were retained and eliminated during the development of the SEM. There is only one factor being excluded from the category of “Regulation Factors”.

Table 15. Finalized factors of opportunities of UAVs adoption in the construction industry

Category	Factors (literature)	Modifications (interviews)	SEM outcomes
Site Surveying	Time-efficient for geophysical surveys	No	Maintained
	High productivity in accessing landslide-prone areas	No	Maintained
	Earthwork volumes determination for road construction	No	Maintained
	Information linkage with simultaneous data measurement and interpretation	No	Maintained
	Automated point-cloud acquisition process	No	Maintained
	Enhancing site surveying via UAV photogrammetry	No	Deleted
	3D modeling and panoramic data from oblique photography	No	Maintained
	UAV-BIM integrates the topography phase	No	Maintained
	3D terrain models in determining rock volume	No	Maintained
	Time efficiency in urban planning and management	No	Maintained
	Greater speed of high-resolution images.	No	Maintained
Site Inspection	Flexibility and maneuverability in accessing hard-to-reach areas	No	Maintained
	Elimination of heavy equipment and elevating platforms	No	Maintained
	Shorter inspection durations via e-inspection technologies	No	Maintained
	Detecting fault points in the transmission lines construction	No	Maintained
	Identifying defects or mutual collisions between components	No	Maintained
Constructing and repairing	Multi-agent automated dry masonry construction	No	Maintained
	Post-construction maintenance and post-disaster reconnaissance	No	Maintained
	Finishing of walls and vertical slopes	No	Maintained
	Lower percentage of non-contributory work	No	Maintained
	Structure repairs in dangerous area	No	Maintained
	Automated assembly of structure made from modular units	No	Maintained
Enhancing 3M Coordination	Generating multiple automated paths for construction rollers	No	Maintained
	Real-time location and measurement tracking of materials	No	Maintained
	Efficient levelling tasks using autonomous dozers	No	Maintained
	Optimizing coordination and collaboration among different trades	No	Maintained
	3D modeling techniques in worker training	No	Maintained
	Generating optimal crane lifting plans via 4D simulation	No	Deleted
	Transporting construction materials on-site	No	Maintained

Table 16. GOF indices of the SM model of challenges of UAVs adoption

Category	Index Name	Index	Attained Values	Acceptance Criteria
Absolute Fit Indices	Discrepancy Chi square	Chisq	78.92	p > 0.01
	Goodness of Fit Index	GFI	0.928	>0.90
	Root Mean Square of Error Approximation	RMSEA	0.074	<0.08
Incremental Fit	Comparative Fit Index	CFI	0.961	>0.90
Indices	Tucker-Lewis Index	TLI	0.929	>0.90
Parsimonious Fit	Chi Square/Degree of freedom	Chisq/df	2.713	<3

Table 17. Finalized factors of challenges of UAVs adoption in the construction industry

Category	Factors (literature)	Modifications (interviews)	SEM outcomes
Safety Concerns	Safety hazards in indoor operations	No	Maintained
	Lack of confidence due to immature technology	No	Maintained
	Operator errors and equipment fatality	No	Maintained
	Extending property damage risks surrounding areas	No	Maintained
Cost Challenges	Additional resource allocation for UAV operators training	No	Maintained
	High capital and operational costs	No	Maintained
	Additional cost in hiring certified UAV operators	No	Maintained

End of Table 17

Category	Factors (literature)	Modifications (interviews)	SEM outcomes
Environmental Factors	Information clutters due to vision obstruction from obstacles	No	Maintained
	Terrain features of varying vegetation degrees	No	Maintained
	CO_2 emissions and noise pollution	No	Maintained
	Severe weather and rugged terrains	No	Maintained
Regulation Factors	Application confined to specific project types	No	Deleted
	Security and privacy concerns from surrounding citizens	No	Maintained
	Risk of data loss due to documentation failures	No	Maintained
	Lack of implementation of UAV regulations by local authorities	No	Maintained
	Heightened liability and legal challenges	No	Maintained
Technical Difficulties	Inaccurate result due to insufficient Ground Control Point (GCP)	No	Maintained
	Limited flight duration due to insufficient battery capacity	No	Maintained
	Interference to wireless technologies within an indoor environment	No	Maintained
	Straining of capabilities due to payload demand	No	Maintained
	Inability to land autonomously in remote locations	No	Maintained

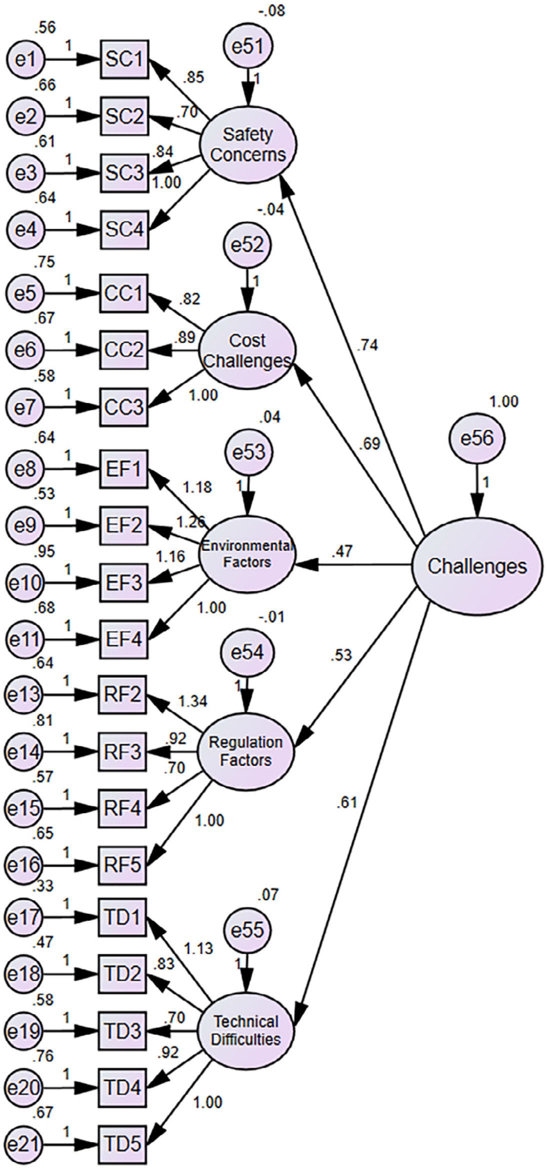

Figure 8. SM model of challenges of UAVs adoption

These outcomes are compatible with other researchers' points, highlighting the five critical aspects that warrant attention when deploying UAVs system at construction sites, which are safety considerations, cost implications, environmental concerns, regulatory requirements, and technical constraints (Chonpatathip, 2023; Nassereddine, 2022; Soon et al., 2024). Furthermore, the results included consistent ideas of the capability of UAVs technology in various specifications, including enhancing site surveying via UAV photogrammetry and eliminating heavy equipment and elevating platforms for site inspection (Matolák et al., 2019; Nassereddine, 2022).

4.3. Framework development

This study aims to achieve one of the objectives, which is to develop a framework for facilitating the implementation of UAVs in the construction industry of Malaysia. The opportunities and barriers of UAVs adoption were assessed through various means, including literature review, semi-structured interview, and questionnaire development, to facilitate the development of framework. The framework in Figure 9 integrated two theoretical foundations, Technology-Organization-Environment (TOE) framework and Iron Triangle of Project Management. TOE framework (Baker, 2012) identifies that technological adoption is influenced by aspects of technological, organizational, and environmental. Technological context reflects the capabilities and limitations of UAVs; organizational context covers the stakeholder roles, such as the project management teams and construction firms, to align with organizational readiness and decision-making; environmental context identifies the challenges of UAVs adoption, including regulation factors and environmental factors. Besides, the project management success metrics are adopted by aligning the project outcomes with the Iron Triangle of Project Management. For instance, the operational efficiency and safety enhancement gained through UAVs implementation achieve the three main pillars of Iron Triangle, including

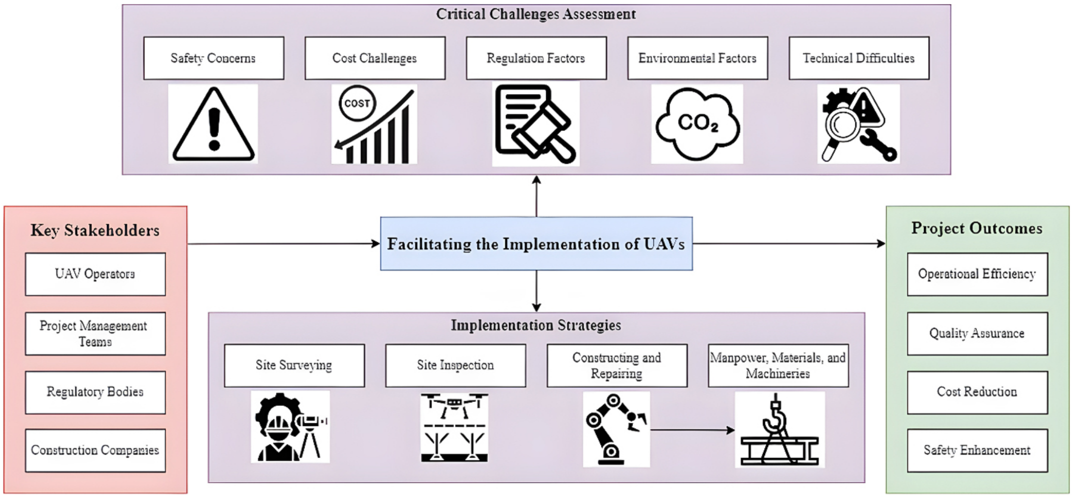

Figure 9. Research framework development on UAVs implementation

cost, time, and quality. This framework serves as a strategic tool for addressing implementation barriers and promoting wider UAVs adoption in Malaysian construction operations.

4.4. Implication of findings

This study provides both theoretical and practical insights that can facilitate the implementation of UAVs in the construction industry. By validating 4 opportunity constructs and 5 challenge constructs, this research extends the UAVs literature in two ways. Firstly, it confirms through CFA that the latent structure of UAVs benefits aligns with distinct operational fields, providing a framework that can be adopted or adapted by future scholars. Secondly, by quantifying relative influence of each construct, the study offers a model that other researchers can integrate into broader technology adoption theories. For instance, "Constructing and Repairing" showed the strongest opportunity loading factor at 0.62, while "Safety Concerns" was the dominant challenge with a factor loading at 0.74.

In terms of practical implications, the results highlight where industry stakeholders such as project managers, contractors, and policymakers should focus their resources to maximize the UAVs return on investment (ROI) and mitigate the barriers. Since "Constructing and Repairing" emerged as the highest impact opportunity, the construction firms should pilot UAV-based masonry, surface finishing, etc. to capture immediate productivity gains. Another example with "Safety Concerns" as the top challenge, organizations must develop reliable flight operation guidelines, training programs and emergency response plans before scaling UAVs application in the industry.

5. Conclusion and recommendations

This research examined the productivity benefits and implementation challenges of UAVs technology in Malaysia's construction sector. The methodology followed a systematic approach, starting with a comprehensive literature review conducted to identify and categorize relevant factors from existing research, forming a theoretical foundation for the opportunities and challenges of UAVs adoption. Following this, industry experts and academicians participated in semi-structured interviews to validate and contextualize the derived factors through practical insights, ensuring alignment with real-world applications in the industry. The interview data underwent qualitative analysis using QDA Miner Lite software to systematically code responses and identify recurring themes. Moving on, the quantitative phase employed SPSS with AMOS extension to analyze survey data through multiple stages, starting from EFA to CFA, and SM development. EFA reduces variables and detects latent constructs, CFA validates the reliability and validity of factor structures, and finally, SM tests hypothesized relationships between the latent variables. The findings were synthesized into a conceptual framework to integrate insights and guide stakeholders in prioritizing UAV adoption strategies. The analysis revealed two key sets of findings regarding UAVs implementation in Malaysia's construction industry. The opportunities were categorized into four main areas, which are "Site Surveying", "Site Inspection", "Constructing and Repairing", and "Enhancing 3M Coordination". The study also identified five principal categories of implementation challenges, including "Safety Concerns", "Cost Challenges", "Environmental Factors", "Regulation Factors", and "Technical Difficulties".

UAVs technology has demonstrated significant potential for improving construction productivity through its diverse applications. While adoption is still in its early phases, UAVs have proven effective in automating certain tasks traditionally performed manually, thereby enabling workforce resources to be redirected toward more complex operations. Despite its benefits, several barriers continue to impede widespread UAVs adoption in construction. Addressing these challenges requires coordinated effort from all relevant stakeholders, each fulfilling their specific responsibilities to create favorable conditions for UAVs integration in the construction sector. Continuous research and innovation are driving significant advancements in the field. The strategic and methodical integration of UAVs is crucial for addressing persistent challenges related to worker well-being and safety, while simultaneously propelling the sector towards enhanced productivity and future growth.

While this research provides valuable insights, there are several limitations to be acknowledged, such as the methodology, geographic specificity, temporal scope, and framework validation. A methodological limitation of this study is that EFA and CFA were conducted on the same dataset, which may lead to inflating of model fit indices. Future research should validate the proposed measurement models using independent samples or cross-validation methods. There may be a limitation of generalizability to other countries due to the findings that are mainly grounded in Malaysia's construction industry. There are regional variations in regulations, environmental conditions, and industry practices for UAVs application. The rapid advancements in UAVs technology such as AI integration may surpass the literature timeframe (2014–2024). Hence, a periodic update on the framework is necessary. Also, despite the theoretically strong conceptual framework, physical testing of framework in real world projects is still required to validate its practical utility.

UAVs technology has demonstrated significant potential for improving construction productivity through its diverse applications. Future research could expand on this study by investigating the long-term economic impacts of UAVs implementation through longitudinal case studies of construction projects that have adopted this technology. As a result, the construction firm, especially the smaller firm, can consider wisely on the UAVs investment by foreseeing the potential rate of return through different adoption approaches. Additional research opportunities include examining the integration of UAVs data with BIM systems and evaluating the effectiveness of different policy frameworks in promoting safe UAVs adoption. Such investigations could provide critical insights into optimizing technological coordination between aerial data collection and digital modeling while also developing regulatory approaches that balance innovation with comprehensive safety protocols. A comparative analysis across different regions or countries could also provide valuable insights into best practices for UAVs implementation in various construction contexts.

Author contributions

All the authors contributed equally to this study.

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Conflicts of interest

The authors declare that they have no conflict of interest.

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APPENDIX

QUESTIONAIRRE

Evaluating the Role of Unmanned Aerial Vehicle (UAV) to Enhance Construction Project Productivity

Dear Sir / Madam,

Questionnaire Contents:

Part 1: General information.

Part 2: Awareness of respondent on application of UAVs in construction industry.

Part 3: Opportunities of UAVs in enhancing the productivity in construction industry.

Part 4: Challenges in implementing UAVs in the construction industry.

Part 1: General Information

Please put (√) on the box in front of the selected choice.

1. Your education level
- Diploma
- BSc
- MSc
- PhD
- Other

2. Your position
- Project Manager
- Project Engineer
- Site Engineer
- Consultant Engineer
- Supervisor
- Architect
- Academician
- Other: ____

3. Your experience in construction works (Years)
- Less than 5
- From 5 to less 10
- From 10 to less 15
- 15 or more

4. Your institution type.
- Consultant
- Contractor
- Client
- Academia
- Other: ____

5. Your institution experience in the construction industry (Years)
- Less than 10
- From 10 to less 20
- From 20 to less 30
- 30 or more

6. Your institution size (number of employees).
- Less than 5
- From 5 to less 20
- From 20 to less 50
- 50 or more

Part 2: Awareness of respondent on application of UAVs in the construction industry.

1. Are you familiar with the application of UAVs in the construction industry?
- I am not familiar with UAVs at all.
- I hear about UAVs but am not fully familiar.
- I am familiar with the application of UAVs in the construction industry.

2. Have you have experience with any UAVs training before?
- Never
- Rarely
- Sometimes
- Very Often
- Always

3. Do your organization provide any training related to UAVs?
- Never
- Rarely
- Sometimes
- Very Often
- Always

4. Have you ever implemented UAVs in your construction projects?
- Never
- Rarely
- Sometimes
- Very Often
- Always

5. How much experience do you have in UAVs implementation?
- 0 year
- 1–2 years
- 3–5 years
- 6–10 years
- More than 10 years

Part 3: Opportunities of UAVs in enhancing the productivity in the construction industry

Meaning	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Symbol	1	2	3	4	5

Opportunities of UAV in the Construction Industry						
No	**Factor 1:** Site Surveying	1	2	3	4	5
1.	UAV is a time-efficient use for geophysical surveys in geological exploration planning.					
2.	UAV ensures high productivity and safety when accessing landslide-prone areas.					
3.	UAV-derived Digital Elevation Models (DEMs) have high time and cost efficiency in determining earthwork volumes.					
4.	UAV establishes information linkage with simultaneous data measurement and interpretation.					
5.	UAV site maps provide automating point-cloud acquisition process by planning navigation paths.					
6.	UAV photogrammetry enhances site surveying process.					
7.	UAV saves time with 3D modeling and panoramic data from oblique photography.					
8.	UAV-BIM integration saves time in the topography phase.					
9.	UAV can calculate rock volume in hard-to-reach dam terrains using 3D terrain models.					
10.	UAV has high time-efficiency in creating databases and 3D maps for urban planning and management.					
11.	UAV has a greater speed of high-resolution images as compared to satellites and manned vehicles.					

Opportunities of UAV in the Construction Industry						
No	**Factor 2:** Site Inspection	1	2	3	4	5
12.	Flexibility and maneuverability of UAV ease the access of hard-to-reach areas.					
13.	UAV eliminates the need to set up heavy equipment and elevating platforms to inspect hazardous areas.					
14.	UAV provides shorter inspection durations via e-inspection technologies.					
15.	UAV can detect fault points in the transmission lines construction easily.					
16.	UAV eases the identification of defects or mutual collisions between components to prevent future rework.					

Opportunities of UAV in the Construction Industry						
No	**Factor 3:** Constructing and Repairing	1	2	3	4	5
17.	UAV can utilize the algorithm for multi-agent automated wall construction in dry masonry construction.					
18.	UAV can improve the productivity of post-construction in building maintenance or post-disaster reconnaissance.					
19.	UAV replaces labor for finishing of walls and vertical slopes.					
20.	UAV has a lower percentage of non-contributory work as compared to traditional approach.					
21.	UAV eliminates the need of human labor for structure repairs in dangerous area.					
22.	UAV enables automated assembly of structure made from modular units.					

Opportunities of UAV in the Construction Industry						
No	**Factor 4:** Enhancing Manpower, Materials, and Machinery (3M) Coordination	1	2	3	4	5
23.	UAV-BIM integration can generate multiple automated paths for construction rollers.					
24.	UAV-RFID integration enables real-time location and measurement tracking of materials on-site.					
25.	Autonomous dozens commanded by UAV live data enables efficient levelling tasks.					
26.	UAV-RFID integration optimizes coordination and collaboration among different trades to avoid excessive works.					
27.	UAV improves the worker productivity by providing training via 3D modeling techniques.					
28.	UAV can generate optimal crane lifting plans via 4D simulation.					
29.	UAV such as multirotor drones can transport construction materials on-site.					

Part 4: Challenges in implementing UAVs in the construction industry

Meaning	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Symbol	1	2	3	4	5

Challenges of UAV in the Construction Industry						
No	**Factor 1:** Safety Concerns	1	2	3	4	5
1.	There are safety hazards for UAV operations in enclosed indoor construction environment.					
2.	There is a lack of confidence in the adoption of UAV due to immature technology.					
3.	Safety risks may occur due to operator errors and equipment fatality.					
4.	UAV operations extend property damage risk to the surrounding areas.					

Challenges of UAV in the Construction Industry						
No	**Factor 2:** Cost Challenges	1	2	3	4	5
5.	Additional complexity and resource allocation are required for UAV operators training.					
6.	The implementation of UAV has high economic challenges due to high capital and operational costs.					
7.	Additional costs are required in hiring certified UAV operators.					

Challenges of UAV in the Construction Industry						
No	**Factor 3:** Environmental Factors	1	2	3	4	5
8.	Information clutters due to vision obstruction from obstacles.					
9.	Inaccuracy results due to terrain features of varying vegetation degrees.					
10.	Environmental impacts encompass CO2 emissions and noise pollution.					
11.	Severe weather and rugged terrains cause flying difficulties of UAV.					

Challenges of UAV in the Construction Industry						
No	**Factor 4:** Regulation Factors	1	2	3	4	5
12.	Application of UAV is confined to specific project types.					
13.	UAV operations lead to security and privacy concerns from surrounding citizens.					
14.	There is a risk of data loss due to documentation failures.					
15.	There is a lack of implementation of UAV regulations by local authorities.					
16.	There are heightened liability and legal challenges for the implementation of UAV.					

Challenges of UAV in the Construction Industry						
No	**Factor 5:** Technical Difficulties	1	2	3	4	5
17.	Insufficient Ground Control Point (GCP) will lead to inaccurate site surveying outcome.					
18.	UAV has a limited flight duration due to insufficient battery capacity.					
19.	There is interference to wireless technologies for application within an indoor construction environment.					
20.	Increased payload demand of UAV will strain its capabilities.					
21.	Inability of UAV to land autonomously in remote locations.					