IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Towards a conceptual framework for application of computer vision in construction cost control

To cite this article: Abdullahi Abdulrasheed Madugu *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1274** 012027

Towards a conceptual framework for application of computer vision in construction cost control

Abdullahi Abdulrasheed Madugu[1,2*], Mohamed Sarajul Fikri[1], Abdulrahman Rilwan Shuaib[2] & Maikano Ahmed Abdullahi[1]

[1]Department of Quantity Surveying, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia.
[2]Department of Quantity Surveying, Faculty of Environmental Design, Ahmadu Bello University, Zaria.

Email: madugu@graduate.utm.my

Abstract. Construction projects have long been plagued by cost overruns, which can significantly impact project outcomes and stakeholder satisfaction. Recent advances in innovative technologies, including computer vision, have shown promise in improving construction project performance. Specifically, computer vision has been recommended as a powerful tool for enhancing cost management processes. Despite its potential, the application of computer vision in cost control for construction projects remains largely unexplored. This paper presents a conceptual framework for effectively leveraging computer vision to improve construction cost control. To achieve this objective, the paper will first review relevant literature on the application of computer vision in construction and construction cost control. The review will examine the existing research, identify knowledge gaps, and provide insights into the potential benefits of using computer vision in cost control. Next, the paper will propose a conceptual framework for integrating computer vision into the construction cost control process. The framework will be based on a thorough analysis of the various aspects of construction cost control and the potential applications of computer vision in each area.

1. Introduction

Construction cost control plays a crucial role in the successful execution of construction projects, allowing stakeholders to effectively monitor and manage expenses throughout the entire construction process. According to the Project Management Institute (PMI) [1] , cost control involves continuously monitoring project costs and managing changes to the cost baseline. The primary objective is to minimize expenses while ensuring the project is completed within the allocated budget, maintaining the desired quality and scope. This necessitates the establishment of a comprehensive system for tracking and analysing costs, identifying potential cost-saving opportunities, and implementing strategies to address any budget overruns. Collaborative efforts among all project stakeholders, including the owner, contractor, and design team, are vital for achieving effective cost control. By implementing a robust cost control system, construction projects can be completed on schedule and within budget, satisfying all parties involved.

Over the years, various cost control tools and techniques have been developed for the sole purpose of improving the efficiency of cost control. These techniques include earned value analysis, unit costing, program evaluation and review technique (PERT), leading parameter method, activity-based ratios, budgetary planning or control, reconciliation of project cost value [2–4]. Furthermore, software packages have also been developed to make the application of these techniques seamless during cost control. These software packages include Microsoft Project, Microsoft Excel, Project Costing System (PCS), Asta Power Project, Primavera Sure trak, WinQs., among others.

While the development of a cost control systems with the ability to track and analyse costs is beneficial, existing traditional approaches, as highlighted by Navon [5], rely on manual data collection, which proves costly, ineffective, and infrequent in facilitating prompt control actions. Additionally, Yismalet and Alemu [6] noted the ineffectiveness of current project cost management practices in controlling project costs. More so, Adjei et al. [7] identified lack of knowledge regarding cost control processes and technologies as a significant challenge in the construction industry.

In recent years, computer vision (CV) has emerged as a valuable tool for managing various aspects of the construction process due to its ability to provide practitioners with detailed digital images and videos capturing crucial information about a construction site, such as object behaviour, location, and site conditions, which can then be leveraged for effective decision-making [8]. Notably, Pal and Hsieh [9] highlight the capability of CV in addressing numerous challenges in construction management. Specifically, CV has been successfully applied in object detection [10], motion tracking[11], action recognition [12], human pose estimation [13], and semantic segmentation [14] on construction sites. However, despite the advantages of CV, there remains a research gap concerning the development of a computer vision-based construction cost control framework that could significantly enhance the overall effectiveness of construction cost control. Such a framework could detect operations deviating from the budget, generate data for assessing variations and changes to the contract.

To address the identified research gap, this paper presents a comprehensive framework for the application of computer vision in construction cost control. The paper initiates by setting the context for computer vision within the construction industry and providing an overview of construction cost control. Subsequently, the proposed framework for utilizing computer vision in construction cost control is introduced, highlighting its key components and functionalities. Through this framework, valuable insights and conclusions are drawn, contributing to the advancement of knowledge in this domain.

2. Computer vision application in construction

Computer vision is an interdisciplinary field of artificial intelligence that focuses on how computing systems can be utilised to acquire meaningful and valuable information from visual components, including digital images, videos, cameras, and closed-circuit television (CCTV) [15]. The objective of computer vision is to replicate the human brain's ability to perceive and comprehend visual information [16]. Through advanced techniques, computer vision enables precise identification and classification of objects, leading to the generation of data-driven recommendations and actionable insights across various domains. Noteworthy applications of computer vision encompass object detection [10], motion tracking [11], action recognition [12], human pose estimation [13], and semantic segmentation [14].

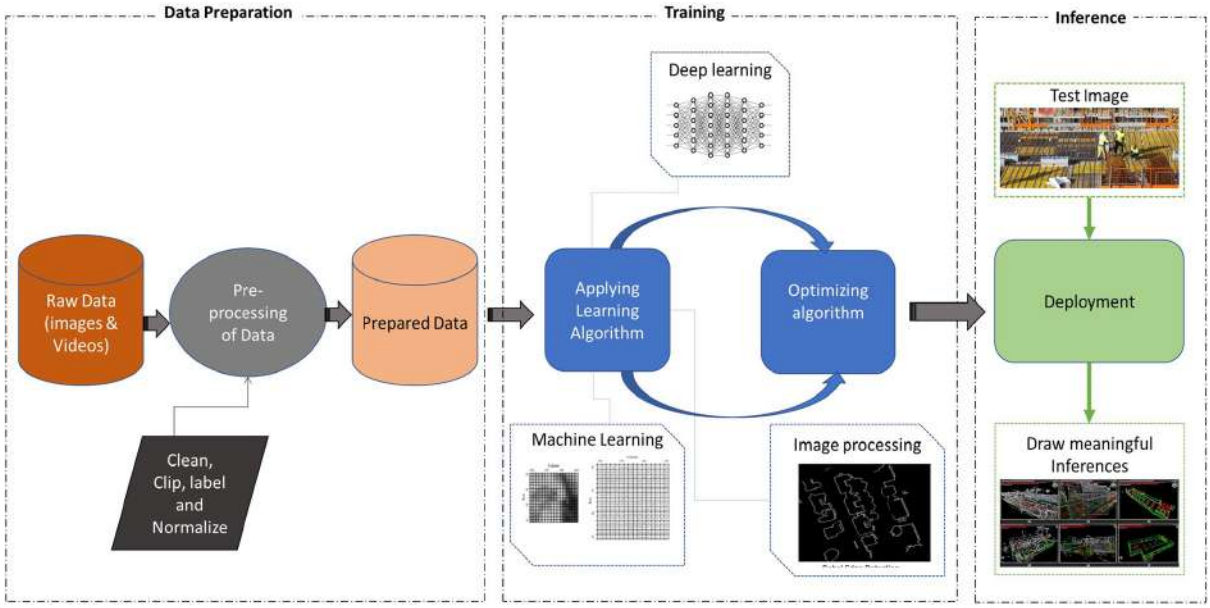

Figure 1. Typical computer vision process [17]**.**

In recent years, the construction sector has witnessed a surge in scholarly exploration concerning computer vision, driven by its promising capabilities for automated and continuous monitoring across various construction fields. Computer vision presents an opportunity to revolutionize engineering and management tasks in construction by facilitating the acquisition, processing, and analysis of digital images, alongside extracting high-dimensional data from the real world to generate valuable information for enhancing decision-making processes [18]. With its capacity to offer practitioners an array of rich digital images and videos encompassing crucial information such as the location and behaviour of objects/entities, as well as site conditions, computer vision emerges as a potent tool in empowering construction management. This wealth of visual data enables project stakeholders to gain deeper insights into the project's prevailing environment, thereby fostering enhanced decision-making and improved management of the construction process [8].

Computer vision has been used to examine specific issues in construction such as quality control [19], productivity tracking [20] safety management [21] and progress monitoring [22,23]. However, limited research has been conducted on the development of a computer vision-based system for construction cost control that facilitates comparisons between actual and budgeted expenses.

3. Construction cost control: an overview

Cost control is an integral part of construction cost management, presenting itself as a formidable challenge for contractors in the current landscape of construction cost management. The implementation of effective cost control practices is essential for the continued existence and advancement of construction organizations. Lu et al. [24] defines cost control as a systematic process aimed at ensuring that the final construction cost aligns with the client's approved budget, achieved through the identification of cost variations, exploration of favourable alternatives, and implementation of appropriate measures. Similarly, Ashworth [25] describes cost control as the practice of confining the client's expenditure within the agreed amount, with the tender sum and final account closely matching the budget estimate. Cost control in construction projects commences early in the project life cycle, spanning from conception to construction and beyond. Its purpose is to enable the project team to continually assess the project's status, promptly identifying any deviations or anomalies. In the event of inconsistencies, cost control empowers the project team to swiftly intervene and restore the project to its desired state, as outlined in the plan [26].

Furthermore, Liang [27] highlights that construction cost control can be categorized into two main areas: pre-contract stage and post-contract stage. The latter involves providing advice to clients and the design team to enable the design to be finalised within the approved budget, while the former refers to processes involved in controlling cost at the construction stage [28]. Controlling costs during the post-contract phase presents its own set of challenges, requiring Quantity Surveyors (QS) to deliver timely and accurate cost advice [28]. Notably, effective post-contract cost control significantly impacts the profitability of both contractors and construction companies [29].

Lu et al. [24] conducted a study highlighting the significance of implementing a robust and efficient system of cost control to ensure project adherence to the allocated budget. The research emphasized the importance of extracting valuable insights from data, enabling the identification of historical patterns as well as the estimation of potential outcomes, including the final account. To achieve comprehensive cost control, several essential processes were identified. These processes include: (a) preparing a comprehensive cost control plan that proactively identifies unfavourable trends and project-related issues; (b) reviewing and approving the work breakdown structure to align it with cost control objectives; (c) creating and monitoring the cash flow to manage financial aspects effectively; (d) continuously monitoring and reporting costs during the construction stage to promptly identify deviations or variances; and (e) initiating and approving financial reports to provide essential information to the owner and contractor management. These measures collectively contribute to an integrated cost control framework, enabling effective project management and informed decision-making.

A multitude of cost control tools and techniques have been developed with the primary objective of enhancing the efficiency of cost control processes. These techniques encompass earned value analysis, unit costing, program evaluation and review technique (PERT/cost), leading parameter method, activity-based ratios, budgetary planning or control, and the reconciliation of project cost value [2–4]. In addition, specialized software packages have been created to facilitate the seamless application of these techniques during cost control activities. Noteworthy examples of such software packages include Microsoft Project, Microsoft Excel, Project Costing System (PCS), Asta Power Project, Primavera Sure track, Bespoke in-house systems, and WinQs.

However, numerous challenges have been reported by researchers within the construction industry. These challenges encompass various barriers, such as the utilization of outdated methods and concepts, limited access to software packages, an excessive focus on outcomes at the expense of the cost control process itself. Interestingly, these barriers appear to be pervasive across studies conducted in diverse locations, highlighting their widespread impact. Notably, Adjei et al. [7] observed that small and medium-sized construction organizations heavily rely on manual, paper-based information, instinct, and past work experiences. Similarly, [30] revealed a disregard for the methodical implementation of cost control during construction project execution. These findings underscore the notion that barriers to effective cost control implementation stem not only from attitudinal factors, as noted by Adjei et al. [7] but also from knowledge and technological constraints. It is worth noting that the absence of real-time information significantly hampers managers' ability to monitor schedules, costs, and other performance indicators, thereby diminishing their capacity to implement cost control measures effectively [31–33].

4. Proposed framework for computer vision-based construction cost control

Figure 2 illustrates the conceptual framework designed for Computer Vision-based Construction Cost Control. The development of this framework involved a thorough evaluation of existing literature studies using the processes of construction cost control described earlier in section 3 and taking a similar approach to applying design science research (DSR) approach to conceptual framework development as specified in [34,35] . In this section, the research delves into the specific details of each of the four primary components of the framework.

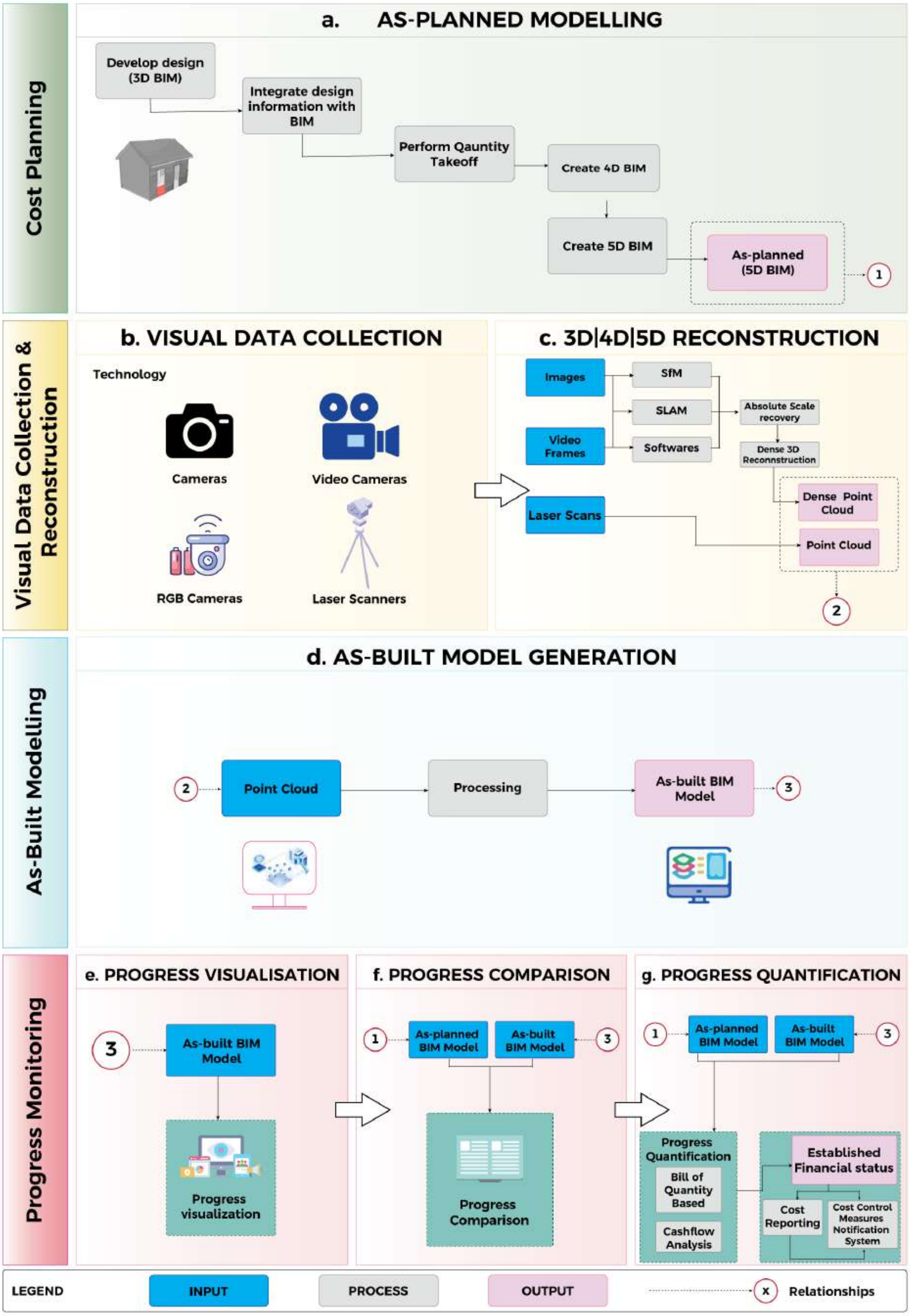

Figure 2. Proposed conceptual framework.

4.1. Cost planning (As-planned modelling

Cost planning in construction projects involves breaking down the total cost limit of the building(s) into specific cost goals for each component of the structure. This process outlines how the design team intends to allocate the available finances among the various constituent parts of the building(s) while ensuring that costs are effectively managed. During the cost planning phase, a building information model (BIM) that contains comprehensive geometric and semantic information can be integrated into a 5D software system to generate a quantity take-off (QTO) list. The QTO list is then linked with an external schedule database, resulting in a schedule-loaded QTO list. By further combining this schedule-loaded QTO list with an external cost database, a cost-loaded project schedule, or cost-loaded timeline, can be produced. This cost-loaded timeline file can be imported back into the 5D platform to generate a 5D BIM model, which becomes a valuable tool for conducting 5D simulations and creating detailed cost plans.

4.2. Visual data collection and 3D reconstruction

The process of data collection for construction progress monitoring relies on the careful selection of appropriate technology, as illustrated in Figure 2(b). A variety of combinations of sensing technologies have been explored as indicated in Figure 2. Vision-based technologies are commonly used for data collection in progress monitoring. These include cameras [36], video cameras [37], laser scanners [38], and RGB cameras [39]. These technologies generate valuable inputs to the monitoring framework in the form of image frames or point clouds, which are essential for analysing the progress of the construction project. Ultimately, the choice of technology will depend on the specific requirements of the construction project, the desired level of detail, the complexity of the site, and the available resources. Selecting the most suitable technology and is crucial for obtaining accurate and relevant data, which is essential for effective construction progress monitoring and decision-making.

After obtaining visual-based input from the previous step, the subsequent stage involves generating a point cloud model through a series of algorithms for 3D/4D/5D reconstruction. Depending on the input source (optical camera images or depth images), different approaches like SfM (Structure-from-Motion) and SLAM (Simultaneous Localisation and Mapping), or RGB-D cameras are used to reconstruct the 3D point cloud, while laser scanners directly provide the 3D point cloud output.

4.3. As-built modelling

The development of As-built building information model (BIM) necessitates a systematic approach encompassing two primary phases: data collection and data modelling. The former involves the meticulous acquisition of as-built conditions, while the latter focuses on generating concise yet comprehensive representations that can be readily integrated with other concurrent processes. At the core of this endeavour lies the profound objective of producing an As-built BIM, a virtual construct aimed at reflecting the actual state of the construction, which may deviate from the original design. This representation serves to provide an accurate and up-to-date depiction of the real-world conditions of the building, thus facilitating informed decision-making and analysis throughout its lifecycle. The existence of an As-planned BIM offers a unique opportunity to actively guide the modelling process. Within this context, the as-built modelling process with As-planned BIM is of twofold interest: firstly, it serves as a geometry checker, meticulously scrutinizing the extent to which the as-built conditions align with the originally envisioned as-designed conditions; secondly, it enables the judicious updating of the extant BIM, ensuring a precise representation of the actualized as-built conditions.

4.4. Progress monitoring

In progress monitoring, it is essential to compare the as-planned model (the intended design or schedule) with the as-built model (the actual construction progress). This comparison can be done either visually or quantitatively to assess the project's progress and identify any deviations or discrepancies between the planned and actual states. The following sub-section discusses sub-processes involved as shown in Figure 2(e,f,g).

4.4.1. Progress visualization: Progress visualisation from an as-built BIM as shown in Figure 2(e) is a valuable tool for understanding and monitoring construction project evolution. The detailed representation of actual building conditions in the as-built BIM allows for visualizations in both non-immersive 3D viewers and immersive Extended Reality (XR) environments, such as Augmented Reality (AR) [40,41], Virtual Reality (VR) [42,43], and Mixed Reality (MR) [44,45]. These visualization methods enable exploring and comparing as-designed and as-built conditions, facilitating better decision-making and collaboration throughout the construction process. As technology advances, these immersive XR environments are becoming increasingly essential for efficient construction project management.

4.4.2. Progress comparison: The integration of as-built and as-planned models during the construction phase of a project, as depicted in Figure 2(f), has been a subject of research since early efforts focused on comparing laser-scanning point clouds with computer-aided drafting (CAD) models. The as-built information, acquired through point clouds, images, or videos, is essential for assessing progress status and determining if the project is behind, ahead, or on schedule. To accomplish this, a 5D BIM model, which includes the time schedule of tasks and cost information, is utilized as the as-planned model. The as-built models are then superimposed on the BIM model to facilitate a comprehensive comparison between the two. Researchers have pursued two primary approaches for the registration process. The first involves manual registration, where experts perform the alignment of the as-built models with the as-planned BIM model [46,47]. The second approach is semi-automated registration, which combines human expertise with automated techniques to achieve alignment [41,48].

4.4.3. Progress quantification: Upon conducting a comparison between the as-planned and as-built BIM to assess the progress of the project, the current financial status of the undertaking is then quantitatively determined, as illustrated in Figure 2(g). This financial evaluation entails utilising the outcomes derived from the comparison of the two models to establish the project's financial standing. It involves comparing the bill of quantities for the completed work items with the entire construction cost, taking into consideration the planned schedule. Additionally, cashflow analysis is performed to further ascertain the financial status of the project. This comprehensive assessment aids in determining whether the project is adhering to the budget, or if there is a likelihood of cost overrun occurrence. By quantitatively analysing the financial data, stakeholders gain insights into the fiscal health of the project and can identify potential areas of concern or inefficiency. Based on the financial evaluation, the project team can implement effective cost control measures to address any budgetary discrepancies and align the project's financial performance with its intended trajectory. Moreover, this process provides valuable guidance for updating the project schedule to account for any financial adjustments and ensure continued financial viability.

5. Conclusion

The research paper presents a comprehensive conceptual framework for the application of computer vision in construction cost control. The significance of cost control in construction projects is highlighted, emphasising the need for effective monitoring and management of expenses throughout the construction process. Existing traditional approaches to cost control are identified as limited due to their reliance on manual data collection, leading to inefficiencies and delayed control actions. The potential of computer vision technology in addressing these challenges is evident. Computer vision's ability to provide detailed digital images and videos capturing critical information about construction sites makes it a valuable tool for decision-making and progress monitoring. Various successful applications of computer vision in construction are outlined, showcasing its versatility and effectiveness.

To bridge the research gap, the proposed conceptual framework comprises four primary components: cost planning, visual data collection and 3D reconstruction, as-built modelling, and progress monitoring. Each component plays a crucial role in enhancing construction cost control. The cost planning component focuses on breaking down the total cost limit of the building(s) into specific cost goals, integrating BIM and 5D software systems to generate quantity take-offs and cost-loaded project schedules. This enables detailed cost planning and simulations, facilitating efficient resource allocation.

Visual data collection and 3D reconstruction rely on vision-based technologies to gather data for progress monitoring. This data is then used to create 3D point cloud models, providing a comprehensive representation of the construction site, and enabling accurate progress assessment.

The as-built modelling component underscores the importance of capturing and representing the actual conditions of the construction through BIM. By comparing the as-built conditions with the as-planned BIM, stakeholders can identify deviations and make informed decisions, ensuring alignment with the project's objectives. The progress monitoring component involves comparing the as-planned model with the as-built model to assess project progress. Progress visualization, comparison, and quantification enable a quantitative determination of the project's financial status. Stakeholders can identify potential budget overruns and implement cost control measures, ensuring projects remain on track.

The proposed framework demonstrates the transformative potential of computer vision technology in revolutionizing construction cost control. By integrating 5D BIM models and leveraging visual data, stakeholders can achieve more accurate and efficient cost management. This research contributes to advancing knowledge in construction cost control and lays the groundwork for further research and implementation of computer vision-based solutions in the construction industry. As technology continues to evolve, the adoption of this framework could lead to improved project outcomes, enabling projects to be completed within budget and schedule while maintaining the desired quality and scope, ultimately benefiting all parties involved in construction projects.

Acknowledgement
This research was supported by Expertise Reinforcement Fund-UTMSPACE PY/2023/00256 of Universiti Teknologi Malaysia. Their support is gratefully acknowledged.

References
[1] Project Management Institute (PMI) 2013 *A Guide to the Project Management Body of Knowledge (PMBOK® Guide).* (Hoboken, NJ: Project Management Institute)
[2] Akeem L B 2017 Effect of Cost Control and Cost Reduction Techniques in Organizational Performance *International Business and Management* **14** 19–26
[3] Olawale Y A and Sun M 2010 Cost and time control of construction projects: Inhibiting factors and mitigating measures in practice *Construction Management and Economics* **28** 509–26
[4] Olawale Y and Sun M 2015 Construction project control in the UK: Current practice, existing problems and recommendations for future improvement *International Journal of Project Management* **33** 623–37
[5] Navon R 2007 Research in automated measurement of project performance indicators *Autom Constr* **16** 176–88
[6] Yismalet A G and Alemu M G 2018 Improving project cost management practice and profitability of domestic contractors in Vadodara *Journal of Emerging Technologies and Innovative Research (JETIR)* **5** 1334–42
[7] Adjei K O, Aigbavboa C O and Thwala W 2017 The Challenges of Cost Control Practice in the Construction Industry: A Literature Review *International Conference on Applied Sciences and Technology (ICAST)* **2020** 14–24
[8] Seo J, Han S, Lee S and Kim H 2015 Computer vision techniques for construction safety and health monitoring *Advanced Engineering Informatics* **29** 239–51
[9] Pal A ands Hsieh S-H 2020 Vision Based Construction Site Monitoring: A Review from Construction Management Point of View *Enabling the Development and Implementation of Digital Twins: Proceedings of the 20th International Conference on Construction Applications of Virtual Reality, Teesside University, 30 Sep.-2 Oct. 2020, Middlesbrough, UK* pp 44–55
[10] Zou Z, Chen K, Shi Z, Guo Y and Ye J 2023 Object detection in 20 years: A survey *Proceedings of the IEEE*
[11] Li C and Lee S 2011 Computer vision techniques for worker motion analysis to reduce musculoskeletal disorders in construction *Computing in Civil Engineering (2011)* pp 380–7

[12] Pareek P and Thakkar A 2021 A survey on video-based human action recognition: recent updates, datasets, challenges, and applications *Artif Intell Rev* **54** 2259–322
[13] Luo H, Wang M, Wong P K-Y and Cheng J C P 2020 Full body pose estimation of construction equipment using computer vision and deep learning techniques *Autom Constr* **110** 103016
[14] Lu W, Chen J and Xue F 2022 Using computer vision to recognize composition of construction waste mixtures: A semantic segmentation approach *Resour Conserv Recycl* **178** 106022
[15] Szeliski R 2022 *Computer vision: algorithms and applications* (Springer Nature)
[16] Rasche C 2019 Computer Vision *Bucharest: Polytechnic University of Bucharest*
[17] Paneru S and Jeelani I 2021 Computer vision applications in construction: Current state, opportunities & challenges *Autom Constr* **132** 103940
[18] Zhong B, Wu H, Ding L, Love P E D, Li H, Luo H and Jiao L 2019 Mapping computer vision research in construction: Developments, knowledge gaps and implications for research *Autom Constr* **107** 102919
[19] Maalek R, Lichti D D and Ruwanpura J Y 2019 Automatic recognition of common structural elements from point clouds for automated progress monitoring and dimensional quality control in reinforced concrete construction *Remote Sens (Basel)* **11** 1102
[20] Spencer Jr B F, Hoskere V and Narazaki Y 2019 Advances in computer vision-based civil infrastructure inspection and monitoring *Engineering* **5** 199–222
[21] Fang W, Ding L, Love P E D, Luo H, Li H, Pena-Mora F, Zhong B and Zhou C 2020 Computer vision applications in construction safety assurance *Autom Constr* **110** 103013
[22] Dimitrov A and Golparvar-Fard M 2014 Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections *Advanced Engineering Informatics* **28** 37–49
[23] Ibrahim Y M, Lukins T C, Zhang X, Trucco E and Kaka A P 2009 Towards automated progress assessment of workpackage components in construction projects using computer vision *Advanced Engineering Informatics* **23** 93–103
[24] Lu W, Lai C C and Tse T 2018 *BIM and Big Data for Construction Cost Management*
[25] Ashworth A 2013 Cost studies of buildings, fifth edition *Cost Studies of Buildings, Fifth Edition* 1–562
[26] Al-Jibouri S H 2003 Monitoring systems and their effectiveness for project cost control in construction *International Journal of Project Management* **21** 45–154
[27] Liang K 2005 *Cost Control in Construction Project of the Site* (Universiti Teknologi Malaysia, Johor Bahru, Malaysia.)
[28] Cunningham T 2017 Cost Control during The Construction Phase of the Building Project : - The Consultant Quantity Surveyor ' s Perspective . *Dublin Institute of Technology* 0–30
[29] Omotayo T S 2017 *Strategic realignment of the post-contract cost control process in the Nigerian construction industry using kaizen* (University of Salford)
[30] Song L 2014 Cost control for small and medium-sized enterprises (SMEs). *J Chem Pharm Res* **6** 409–12
[31] Reja V K, Varghese K and Ha Q P 2022 Computer vision-based construction progress monitoring *Autom Constr* **138** 104245
[32] Teizer J 2015 Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites *Advanced Engineering Informatics* **29** 225–38
[33] Howell G A 1999 What is Lean Construction *In Proceedings IGLC* p
[34] Omair B and Alturki A 2020 An improved method for taxonomy development in information systems *Int. J. Adv. Comput. Sci. Appl* **11** 535–40
[35] Barth L, Ehrat M, Fuchs R and Haarmann J 2020 Systematization of digital twins: Ontology and conceptual framework *Proceedings of the 2020 The 3rd International Conference on Information Science and System* pp 13–23
[36] Golparvar-Fard M, Pena-Mora F and Savarese S 2015 Automated progress monitoring using unordered daily construction photographs and IFC-based building information models *Journal of Computing in Civil Engineering* **29** 4014025

[37] Kazemian A, Yuan X, Davtalab O and Khoshnevis B 2019 Computer vision for real-time extrusion quality monitoring and control in robotic construction *Autom Constr* **101** 92–8
[38] Braun A, Tuttas S, Stilla U and Borrmann A 2018 Process-and computer vision-based detection of as-built components on construction sites *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* vol 35 (IAARC Publications) pp 1–7
[39] Dino I G, Sari A E, Iseri O K, Akin S, Kalfaoglu E, Erdogan B, Kalkan S and Alatan A A 2020 Image-based construction of building energy models using computer vision *Autom Constr* **116** 103231
[40] Xu J and Moreu F 2021 A review of augmented reality applications in civil infrastructure during the 4th industrial revolution *Front Built Environ* **7** 640732
[41] Golparvar-Fard M, Peña-Mora F and Savarese S 2011 Integrated sequential as-built and as-planned representation with D 4 AR tools in support of decision-making tasks in the AEC/FM industry *J Constr Eng Manag* **137** 1099–116
[42] Rahimian F P, Seyedzadeh S, Oliver S, Rodriguez S and Dawood N 2020 On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning *Autom Constr* **110** 103012
[43] Buhammood A H, Abanda H, Garstecki P, Manjia M B, Pettang C and Abdullahi A M 2020 Coupling BIM and game engine technologies for construction knowledge enhancement *International Journal of Gaming and Computer-Mediated Simulations (IJGCMS)* **12** 38–63
[44] Khairadeen Ali A, Lee O J, Lee D and Park C 2021 Remote indoor construction progress monitoring using extended reality *Sustainability* **13** 2290
[45] Kopsida M and Brilakis I 2020 Real-time volume-to-plane comparison for mixed reality–based progress monitoring *Journal of Computing in Civil Engineering* **34** 4020016
[46] Memon Z A, Majid M Z A and Mustaffar M 2005 An automatic project progress monitoring model by integrating auto CAD and digital photos *Computing in Civil Engineering (2005)* pp 1–13
[47] Zhang C and Arditi D 2013 Automated progress control using laser scanning technology *Autom Constr* **36** 108–16
[48] Bosché F 2012 Plane-based registration of construction laser scans with 3D/4D building models *Advanced Engineering Informatics* **26** 90–102