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Drivers and Barriers to Adopting Smart Construction Technologies by Small and Medium Enterprises

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ABSTRACT

The construction industry is undergoing rapid digital and technological transformation, but Small and Medium Enterprises (SMEs) often face distinct operational and financial constraints that limit their uptake of Smart Construction Technologies (SCT). Despite government initiatives and growing industry momentum, many SMEs remain hesitant or only partially engaged with SCT. This study aims to identify the key drivers and barriers to SCT adoption among Singaporean SMEs and to propose strategies to overcome these barriers. This study employed a mixed-methods approach - quantitative data were collected via an online survey of construction professionals (53 valid responses: 34 from SMEs and 19 from larger firms) and qualitative data were obtained through semi-structured interviews with three (3) experienced industry practitioners. The survey data collected was analysed using Jeffreys's Amazing Statistics Program (JASP) for chi-square tests, Shapiro-Wilk normality tests and Wilcoxon signed-rank tests. Interview transcripts were coded thematically to identify the most salient drivers and barriers. The findings reveal that 94% of responding SMEs have initiated SCT adoption, yet full integration into operations is limited. This study identified 15 significant drivers and 13 barriers. Major drivers include financial incentives, regulatory mandates and demonstrable performance gains. On the other hand, key barriers are high costs, resource and skill shortages and practical implementation challenges. Qualitative data confirmed these trends and highlighted SMEs' conservative culture and survival-oriented mindset as additional factors. These results indicate that while SMEs recognise the potential of SCT, adoption remains partial due to cost, capability and cultural constraints. Addressing these issues through targeted financial support, accessible training and fostering collaborative digital ecosystems can accelerate adoption. By focusing explicitly on SMEs, this study fills a research gap and provides empirical evidence of

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SME-specific factors in SCT adoption. The actionable insights will help policymakers, industry leaders and technology providers tailor interventions to support SME digital transformation.

INTRODUCTION

The Built Environment (BE) industry, encompassing construction and related sectors, is a global economic powerhouse, valued at over $17 trillion in 2025 (The Business Research Company, 2025). In Singapore, strong government policies such as the Integrated Planning and Design (IPD) and Advanced Manufacturing and Assembly Initiatives under the Industry Transformation Map drive innovation and technology adoption in construction. Smart Construction Technologies (SCT) which is defined in this study as digital and technological innovations that enhance the efficiency, safety and environmental performance of construction activities through automation, real-time data analytics, and integrated project management, refer to digital and technological solutions, including Building Information Modelling (BIM) for planning, design and management through a collaborative process, Internet of Things (IoT) for real-time data from sensors on equipment and sites, Artificial Intelligence (AI) for predictive analysis, drones for site surveys and progress monitoring, robots for automated tasks like excavation and bricklaying, and three-dimensional (3D) printing for on-site component fabrication, undertaken by projects around the world (Autodesk & Deloitte Access Economics, 2024; Casini, 2022; Chen et al., 2021; Chen et al., 2022; Leng et al., 2023; Mankins, 1995; Maskuriy et al., 2019; Oesterreich & Teuteberg, 2016; Parasuraman, 2000; Reichenbach & Kromoser, 2021; The Business Research Company, 2025; Van der Heijden, 2023; Zhang et al., 2023). In practice, Singapore's construction industry has begun integrating SCT to enhance efficiency and sustainability (Hwang et al., 2022; Ministry of National Development, 2024). However, adoption remains uneven. Large contractors and public projects often lead in Information and Communication Technology (ICT) and prefabrication, while many SMEs struggle with high costs, limited expertise and integration challenges (Amusan et al., 2021; Gamage et al., 2020; Hashmicro, 2024; Prasanna et al., 2019).

In this context, understanding how SMEs, which are defined as enterprises with annual income under $100 million or fewer than 200 employees (Amusan et al., 2021; Gamage et al., 2020; Hashmicro, 2024; Prasanna et al., 2019), adopt SCT is crucial. SMEs play a vital role in the construction value chain as subcontractors, suppliers and niche service providers, but they face unique challenges, such as limited access to financing, talent shortages and conservative organisational culture, that can hinder technology uptake (Amusan et al., 2021; Gamage et al., 2020; Ofori et al., 2020; Prasanna et al., 2019). There is a clear research gap on SME-specific drivers and barriers to SCT adoption. Accordingly, this study aims to explore those factors in Singapore and recommend how to support SMEs in the digital and technological transition.

To meet these aims, this study poses the following research objectives: to determine SMEs' roles and challenges in construction; to identify the SCT types (e.g. BIM, IoT, AI, drones, robotics) relevant to SMEs and their practical benefits; to examine organisational factors (including leadership, culture and change management) that affect SME adoption of SCT; to investigate current SCT usage trends among SMEs and their adoption intentions; to identify the key drivers (e.g. government incentives, client demands) and barriers (e.g. cost, skill gaps, resistance to change) influencing SME adoption; and to recommend strategies and policy supports to overcome these barriers. By integrating these objectives, this study will inform strategies that help Singaporean SMEs become more competitive, productive and sustainable through SCT adoption.

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To address the research gap regarding how SMEs in the construction sector manage digital transformation and disruptive technologies, this study seeks to explore the factors that drive and impede the adoption of SCT by SMEs in Singapore's construction sector.

The findings from this research aim to provide context-specific evidence and framework explaining the determinants of SCT adoption among construction SMEs in Singapore and inform strategies that encourage and support greater adoption of SCT among local SMEs, thereby enhancing their competitiveness, productivity and sustainability.

LITERATURE REVIEW

A comprehensive literature review using databases such as Scopus, Google Scholar, ScienceDirect, and JournalStorage (JSTOR) was conducted to map out the current state of SCT adoption in construction, with emphasis on SMEs and the Singapore context (Hashmicro, 2024; Hwang et al., 2022; Ofori et al., 2020). This study focused on drivers (factors that encourage adoption) and barriers (factors that hinder adoption) identified in prior studies of digitalisation and technological adoption in the construction industry.

To ensure a thorough exploration of the subject, a range of keywords was used, including 'adoption of smart construction technologies', 'drivers of adoption', 'barriers to adoption', 'construction industry in Singapore', 'smart technologies', and 'digital transformation in construction'. These keywords were strategically applied to capture a wide array of studies addressing both enabling factors – the drivers, and challenges – the barriers, faced by the stakeholders in the construction sector. The selected articles provided insights into the technological, organisational and regulatory factors that influence adoption.

The construction value chain includes various segments such as land planning, development, construction, engineering, specialty trades, materials and maintenance and SMEs play a crucial role in this ecosystem (Amusan et al., 2021; Gamage et al., 2020; Hashmicro, 2024; Prasanna et al., 2019). In many markets, including Singapore, SMEs are the backbone of the construction sector and provide essential services such as supplying materials and specialised services, often supporting larger firms in executing complex projects (Amusan et al., 2021; Gamage et al., 2020; Hashmicro, 2024; Prasanna et al., 2019). Despite their importance, SMEs face several challenges, including market competition, financial constraints and the need for technological adaptation. The adoption of SCT offers SMEs the potential to overcome these challenges, improving productivity, project management and sustainability. However, the integration of SCT is often hindered by barriers such as limited access to financing, insufficient technical knowledge and resistance to change (Amusan et al., 2021; Gamage et al., 2020; Hashmicro, 2024; Prasanna et al., 2019). Understanding the key drivers that encourage SCT adoption as well as the barriers that hinder it, is essential for devising strategies that enable SMEs to harness the full potential of these technologies and strengthen their positions within the industry. This literature review explores the significance of SMEs in the construction sector and examines the various factors influencing the adoption of SCT, with a focus on the drivers and barriers unique to SMEs.

Significance and Role of SMEs

SMEs are vital to the economy, particularly in emerging markets, contributing to growth, job creation, and local industry development. They represent over 90% of businesses globally and provide 50 to 60% of employment (Amusan et al., 2021; Gamage et al., 2020; Hashmicro, 2024; Prasanna et al., 2019). Their adaptability drives innovation and competition, supporting larger enterprises through supply chains and subcontracting.

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In Singapore's construction sector, SMEs are essential as contractors, subcontractors and service providers, supporting larger firms and ensuring sector growth. The Singaporean government supports SME development through initiatives to help them thrive in the competitive global market, ensuring their continued role in economic success (Reichenbach & Kromoser, 2021).

Technology Adoption in the Built Environment Industry

The construction industry has long faced challenges such as labour shortages, safety concerns, and issues related to productivity and quality control. The construction industry also historically lags in IT adoption due to fragmentation and risk aversion (Autodesk & Deloitte Access Economics, 2024; Chen et al., 2021; Maskuriy et al., 2019; Oesterreich & Teuteberg, 2016; Van der Heijden, 2023). To address these, researchers have explored emerging technologies throughout the construction life cycle, from design to operations (Autodesk & Deloitte Access Economics, 2024; Chen et al., 2021; Maskuriy et al., 2019; Oesterreich & Teuteberg, 2016; Van der Heijden, 2023).

SCT, including BIM, IoT, robotics, drones, and AI are transforming the industry and enhancing safety, productivity and resource efficiency through real-time monitoring, automation, and predictive analysis. Technologies like Digital Twins, Additive Manufacturing and Blockchain also optimise planning, project management and construction precision. Despite their potential, the industry has been slow to adopt SCT, especially compared to others during the Coronavirus Disease 2019 (COVID-19) (Law et al., 2022; Ofori et al., 2020; Osunsanmi et al., 2020). This lag contributes to ongoing issues like labour shortages, poor project quality and inefficiencies. This study aims to identify the drivers and barriers for SCT adoption by SMEs.

Last but not least, it should be pointed out that smart construction technologies can be adopted at different pace due to technology maturity and technology adoption readiness. Therefore, adoption rate varies across countries, sectors, organisations, and technologies (Autodesk & Deloitte Access Economics, 2024; Mankins, 1995; Parasuraman, 2000; The Business Research Company, 2025).

Drivers and Barriers to the Adoption of SCT

Key drivers identified included cost-efficiency, improved productivity, government support and the increasing demand for sustainable practices (Ayodele & Kajimo-Shakantu, 2021; Bello et al., 2021; Law et al., 2022; Liao & Teo, 2018; Nagy et al., 2021; Nnaji & Karakhan, 2020; Osunsanmi et al., 2020; Seyman-Guray & Kismet, 2023). Barriers discussed in the literature included high initial investment costs, lack of skilled workforce, resistance to change, and concerns about technology integration (Bello et al., 2021; Delgado et al., 2019; Law et al., 2022; Nagy et al., 2021; Nnaji & Karakhan, 2020; Ofori et al., 2020; Osunsanmi et al., 2020; Prabhakar et al., 2023; Seyman-Guray & Kismet, 2023).This literature review establishes the foundational knowledge necessary for understanding the current landscape of smart construction technologies in Singapore and identifies gaps in the research, offering a basis for the study's focus and subsequent data collection.

Scott's Institutional Framework was instrumental in categorising the drivers and barriers to the adoption of SCT in the context of SMEs within the construction industry. This framework provides a comprehensive understanding of institutions as enduring structures that shape and influence social behaviour, guiding decisions and practices within organisations (Scott, 2014). The framework identifies three (3) key pillars that influence SCT adoption: the regulative, normative and cultural-cognitive pillars. The regulative pillar encompasses formal rules, regulations, and policies that govern organisational behaviour, focusing on ensuring compliance through legal sanctions and incentives (Scott, 2014). In the

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case of SCT adoption, this pillar includes government regulations, legal standards and industry policies that shape the use and implementation of these technologies. The normative pillar emphasises social values, norms and expectations, influencing what is deemed appropriate or desirable within society or industry. It shapes behaviours by aligning them with social obligations and in the context of SCT, reflects industry expectations for innovation, sustainability and technological advancement in construction practices. The cultural-cognitive pillar refers to the shared beliefs, mental models and informal understandings that guide how individuals and organisations interpret reality. This pillar highlights the influence of industry-wide assumptions and professional experiences in shaping decisions around technology adoption. Prevailing attitudes and deeply ingrained practices often impact the willingness to embrace new technologies, with SCT adoption influenced by these subconscious beliefs about their utility and (Scott, 2014).

Our study builds on this foundation to empirically identify which drivers and barriers are most critical in Singaporean SMEs and how they compare to prior findings. Using Scott's framework to categorise the drivers and barriers provides a structured approach to understanding the complexities SMEs face in adopting SCT. It enables a deeper analysis of the factors influencing the decision-making process and serves as a foundation for formulating strategies to facilitate the adoption of these technologies in the construction industry. Tables 1 and 2 present the cross-referencing of identified drivers and descriptions of drivers across various literature sources, respectively. Similarly, Tables 3 and 4 present the cross-referencing of identified barriers and descriptions of barriers across literature sources.

Table 1. Cross-referencing of Drivers Across Literature Sources

Drivers	(Oesterreich & Teuteberg, 2016)	(Liao & Teo, 2018)	(Maskuriy et al., 2019)	(Prasanna et al., 2019)	(Nnaji & Karakhan, 2020)	(Ayodele & Kajimo-Shakantu, 2021)	(Bello et al., 2021)	(Reichenbach & Kromoser, 2021)	(Casini, 2022)	(Law et al., 2022)	(Hwang et al., 2022)	(Autodesk & Deloitte Access Economics, 2023)	(Leng et al., 2023)	(Seyman-Guray & Kismet, 2023)	(Autodesk & Deloitte Access Economics, 2024)	Identified from Singapore's context
RD1	✓	✓							✓		✓					
RD2	✓								✓							
RD3																✓
RD4	✓						✓	✓	✓	✓		✓	✓	✓	✓	
ND5		✓	✓		✓				✓			✓			✓	
ND6	✓		✓					✓	✓	✓			✓		✓	
ND7			✓			✓	✓	✓	✓	✓		✓		✓	✓	
ND8		✓		✓		✓	✓	✓	✓			✓	✓	✓	✓	
ND9	✓		✓			✓	✓	✓	✓	✓			✓	✓	✓	
ND10	✓	✓					✓		✓		✓					
ND11		✓	✓	✓		✓				✓		✓				
ND12	✓	✓			✓											
ND13					✓											
CCD14		✓					✓					✓				
CCD15		✓		✓	✓						✓					

Source: Authors (2024)

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Table 2. Defining Drivers Influencing Adoption of SCT

Code	Drivers	Influence on SCT adoption and categorisation within the institutional framework (brief description)
RD1	Government grants	Government incentives and regulations drive SCT adoption by increasing awareness and compliance.
RD2	Government initiative in project mandates/ specifications	
RD3	Government-hosted resources and support	
RD4	Safety enhancements	Safety improvements through SCT enhance compliance and reduce penalties.
ND5	Client expectations and demand	Client demand for innovation and efficiency influences SCT adoption.
ND6	Achieving greater sustainability standards	Environmental responsibility and energy efficiency motivate SCT use.
ND7	Quality Enhancement	Industry standards and efficiency expectations promote SCT adoption.
ND8	Enhanced workforce productivity	
ND9	Cost savings with optimised operations	
ND10	Enhanced collaboration and communication among stakeholders	
ND11	Market competitive advantage	
ND12	Availability of trusted guidance and technical support	Technical support and guidance aid adherence to best practices.
ND13	Availability of periodic payment for adoption of technology	Flexible payment schemes ease SCT adoption and build confidence.
CCD14	Adaptability to accommodate organisational growth and increasing project complexities	Growth strategies and shared beliefs shape willingness to adopt SCT.
CCD15	Present examples of successful case study/use cases	Successful case studies strengthen shared beliefs in SCT's value.

Source: Authors (2024)

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Table 3. Cross-referencing of Barriers Across Literature Sources

Barriers	(Oesterreich & Teuteberg, 2016)	(Delgado et al., 2019)	(Maskuriy et al., 2019)	(Prasanna et al., 2019)	(Nnaji & Karakhan, 2020)	(Osunsanmi et al., 2020)	(Saka & Chan, 2020)	(Ayodele & Kajimo-Shakantu, 2021)	(Bello et al., 2021)	(Abuwarda et al., 2022)	(Casini, 2022)	(Law et al., 2022)	(Hwang et al., 2022)	(Autodesk & Deloitte Access Economics, 2023)	(Prabhakar et al., 2023)	(Seyman-Guray & Kismet, 2023)	(Autodesk & Deloitte Access Economics, 2024)	(Liang et al., 2024)	Identified from Singapore's context
RB1	✓		✓		✓			✓					✓		✓			✓	
RB2	✓		✓						✓	✓			✓						
RB3																			✓
RB4	✓	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓	✓				
RB5	✓		✓		✓			✓	✓	✓			✓					✓	
NB6	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓		
NB7		✓		✓		✓	✓	✓	✓			✓	✓			✓			
NB8	✓	✓	✓	✓	✓	✓		✓	✓				✓	✓		✓	✓		
NB9	✓	✓	✓		✓	✓	✓	✓		✓		✓	✓			✓			
NB10		✓			✓	✓		✓	✓										
CCB11	✓	✓	✓	✓	✓		✓					✓	✓		✓			✓	
CCB12		✓		✓							✓						✓	✓	
CCB13	✓	✓	✓		✓	✓	✓	✓						✓			✓		

Source: Authors (2024)

Table 4. Defining Barriers Influencing Adoption of SCT

Code	Barriers	Influence on SCT adoption and categorisation within the institutional framework (brief description)
RB1	Uncertainty surrounding legal and contractual usage	Unclear legal liability for SCT errors causes hesitation in adoption.
RB2	Compliance with regulatory standards	
RB3	Lack of long-term allocation of resources from governing bodies	High ongoing costs for maintenance, upgrades and training deter adoption.
RB4	Lack of reference architecture, guidelines and support from stakeholders	Lack of clear frameworks and accountability creates uncertainty in SCT use.
RB5	Data security and privacy concerns	Data security and privacy concerns hinder SCT adoption.
NB6	High investment and implementation cost	High acquisition and implementation costs with unclear ROI limit adoption.
NB7	Challenges in implementing technology on site	Complex site conditions and inconsistent stakeholder expertise reduce SCT integration.
NB8	The need to enhance existing workforce expertise to address skill gaps	Skills gap and ageing workforce impede SCT adoption.

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NB9	The need to integrate with, improve, or upgrade current systems and processes	Interoperability and standardisation issues restrict SCT integration.
NB10	Long-term cost associated with use, continuous maintenance and upgrades	Long-term operational costs discourage sustained SCT adoption.
CCB11	Uncertainty with associated benefits and potential risks	Lack of proven ROI and benchmarks leads to risk-averse attitudes.
CCB12	Shortage of skilled and digitally competent workforce	Negative industry image and ageing workforce limit digital talent recruitment.
CCB13	Organisational or individual reluctance to shift from traditional methods	Organisational and employee resistance to change slows SCT adoption.

Source: Authors (2024)

RESEARCH METHODOLOGY

To address the research gap regarding how SMEs in the construction sector manage digital transformation and disruptive technologies, this study adopts a structured, four-stage research methodology to ensure a comprehensive and evidence-based understanding of Smart Construction Technology (SCT) adoption among SMEs in Singapore's construction sector. By integrating both qualitative and quantitative techniques, the study captures a broad and nuanced perspective of the drivers, barriers and organisational factors influencing SCT uptake.

Stage 1: Research and Identification

This stage begins with an extensive literature review to frame the research problem and objectives clearly. The review encompasses academic articles, government publications and industry reports related to construction digitalisation, SME innovation and technology adoption models. The aim is to uncover existing knowledge gaps and synthesise key variables influencing SCT adoption. These variables, such as regulatory pressures, organisational readiness, technology awareness and financial capacity, are categorised using Scott's Institutional Theory (regulative, normative and cultural-cognitive pillars) and summarised in Tables 1 to 4 for clarity and reference. This theoretical lens supports a structured understanding of how institutional factors shape SME behaviour regarding technology adoption.

Stage 2: Conceptual Framework Development

Insights gained from the literature are used to develop a conceptual framework that links organisational characteristics, institutional pressures, drivers and barriers to SCT adoption behaviour. This framework guides the formulation of key considerations and factors such as leadership commitment, perceived usefulness of SCT, funding availability and workforce readiness. The framework serves as the analytical foundation for the survey and interview instruments used in the data collection stage.

Stage 3: Data Collection and Analysis

A listing of Registered Contractors in Singapore was downloaded and filtered using Contractor Grade and Work-head, paid-up capital and financial metrics (i.e. under $100 million) and number of employees (i.e. less than 200 employees) to identify Construction SMEs registered in Singapore.

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A mixed-method approach is employed to obtain robust and triangulated data. The themes and sections of the survey and interviews include: Organisational Context, Drivers, Barriers, and the Future Outlook and Recommendations.

(i) Quantitative data was targeted at industry practitioners (engineers, managers, and directors) in construction and related services, gathered through an online survey administered between August and mid-September 2024. Distribution channels included email outreach, LinkedIn networks and snowball sampling via industry contacts. The companies can be found from BCA Directory, an online directory of registered contractors, licensed builders, facilities management companies and construction-related suppliers. Inclusion criteria were currently working in the built environment sector and involved in project planning or execution.

(ii) Qualitative data was collected via semi-structured interviews with three (3) key stakeholders in early October 2024: a director from a multinational construction firm (MNC), a Deputy Director from a local SME and a Deputy Manager from a statutory board or developer, after preliminary analysis of quantitative data collected from the survey earlier. These interviews provided deeper insights into industry realities, validated survey trends, and contextualised quantitative findings.

The data was analysed using Jeffreys's Amazing Statistics Program (JASP) statistical software, employing the following statistical tests:

(i) Chi-Square and Cramer's V to examine associations between categorical variables.

(ii) Shapiro-Wilk Test to assess data normality.

(iii) Wilcoxon Signed-Rank Test to evaluate paired differences in perception-related items.

This analytical approach allowed the study to identify statistically significant relationships and patterns in SCT adoption behaviour among SMEs.

Stage 4: Evaluation and Conclusion

In the final stage, findings from the survey and interviews are synthesised to answer the research questions and validate the prepositions. The analysis highlights key enabling and inhibiting factors, usage trends and organisational influences. Limitations of the study, such as sample size, potential biases in survey distribution and time constraints are acknowledged. The study concludes by offering evidence-based recommendations for SMEs, industry bodies and policymakers and outlines directions for future research to extend the understanding of SCT adoption in other contexts or sub-sectors of the built environment.

DATA ANALYSIS AND DISCUSSION

The surveys were distributed to the target respondents via email and LinkedIn. Over a period of six (6) weeks, 66 responses were collected. Among the responses received, 53 were valid, while 13 were considered invalid. Invalid responses included those from individuals who did not fit the targeted profession group or did not provide consent to participate in the survey.

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Among all respondents, 34 were classified as SMEs and 19 as non-SMEs. For the primary purpose of this study, further analysis will focus on the 34 responses obtained from SMEs. With a sample size of 34, this study met the criteria for representativeness according to the Central Limit Theorem, which suggests that a sample size of 30 respondents or more is sufficient for reliable statistical analysis for a meaningful and insightful analysis (Hasofer, 2014). The 19 non-SMEs respondents enhance the study's balance and comprehensiveness by providing a benchmark for comparison. Larger firms often have greater financial, technical and human resources to adopt Smart Construction Technologies (SCT). By contrasting their practices with SMEs, the study can identify gaps, best practices, and contextual differences in adoption readiness. This dual and comparative perspective strengthens the analysis, revealing whether observed challenges are unique to SMEs or industry-wide and supports the development of more targeted policy and capability-building recommendations for different firm sizes within the construction ecosystem.

Additionally, three (3) in-depth interviews offer qualitative and nuanced insights to complement the survey findings. Having three (3) interviews enhances findings from questionnaire surveys by providing deeper insights, clarifying ambiguous responses and uncovering new perspectives that surveys might miss. For instance, interviewees were asked to comment on identified top and bottom drivers and barriers. Interviews allow for follow-up questions, helping to understand motivations and context behind responses. They also validate survey data by cross-checking consistency and identifying any gaps or biases in the survey design. Some Verbatim from interviewees on barriers and drivers to adoption of SCT are highlighted in this Section to complement discussion on the literature review and survey findings. They , i) bridge theory and practice by offering real-life insights to support or challenge theoretical frameworks discussed in the literature review, ii) contextualise survey data when they add depth to quantitative findings by explaining the 'why' behind patterns and findings, iii) highlight contrasts when practices in the industry diverge from existing studies or surveys, and iv) humanise the data providing personal perspectives that make abstract or statistical results more relatable and impactful.

Roles and Challenges Faced by SMEs

SMEs play a vital role in construction supply chains, delivering specialised services, labour and innovation. However, they face persistent challenges and constraints which hinder their ability to leverage SCT effectively. Table 5 highlights key challenges faced by SMEs and non-SMEs based on descriptive statistics. SMEs struggle most with market competition from local large firms (Rank 1) and financial constraints (Rank 2), indicating difficulties in competing and securing funding. In contrast, non-SMEs are most affected by staff turnover (Rank 1) and a lack of workers with suitable expertise (Rank 2), suggesting talent retention and skill gaps as major concerns. Both groups face common issues such as competition from foreign entrants/ MNCs and regulatory compliance. These findings highlight the need for strategic support and financial incentives to encourage technology adoption among SMEs, enabling them to remain competitive in an evolving market. Additionally, this highlights the differences between SMEs and non-SMEs in their focus on organisational challenges, potentially leading to differences in attitudes and factors influencing SCT adoption. This justifies the study's aim of examining SCT adoption primarily from the SME perspective.

Table 5. Test Statistics for Industry Challenges

Challenges	SMEs Mean	SMEs Std Dev	SMEs Rank	Non-SMEs Mean	Non-SMEs Std Dev	Non-SMEs Rank
Market competition with local large firms	3.70	0.90	1	3.26	1.21	4
Financial constraints	3.58	0.82	2	2.79	1.00	5

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Market competition with foreign entrants/MNCs	3.42	0.95	3	3.32	1.26	3
Staff turnover	3.36	0.88	4	3.58	0.82	1
Lack of workers with suitable expertise	3.36	0.85	4	3.47	0.94	2
Economic uncertainty	3.33	0.91	5	3.11	0.91	4
Regulations and compliance requirements	3.21	0.91	6	3.32	1.17	3
Supply chain challenges	3.18	0.94	7	3.26	1.16	4

Source: Authors (2024)

Types and Benefits of SCT and Their Usage Among SMEs

SCT adoption can enhance project accuracy, safety, resource efficiency, and real-time decision-making, ultimately improving productivity and sustainability. The survey reveals a high rate of such SCT usage among SMEs, with 30 out of 34 respondents (94.12%) indicating that their organisation uses SCT, while only 2 respondents (6%) reported no usage as shown in Figure 1. More common types of SCT adopted by SMEs include BIM, IoT, and cloud computing. However, over 80% of the respondents indicated that SCT have not been extensively used in their organisations. The SMEs that reported extensive use of SCT are mostly architectural and civil engineering firms. This is likely due to the nature of their work, which often involves planning, visualisation and simulations, necessitating the use of SCT such as cloud computing and BIM. This is consistent with Casini's (2022) findings that the use of BIM and cloud-based CDE plays a crucial role in C4 and serves as the foundation for many SCT commonly utilised by architects and engineers. The findings indicate that while SMEs have adopted SCT to some extent, its usage remains limited and not fully optimised. This suggests that although some implementation has taken place, SCT is not yet deeply integrated into the core operations of most SMEs. Looking ahead, nearly 50% of SMEs plan to increase SCT investment, especially in civil engineering and general building works. However, financial constraints remain a key barrier, though government initiatives support adoption. While many SMEs have strategies for SCT implementation and regularly reviews advancement in SCT, some remain hesitant due to financial risks and conservatism.

Comparison of SCT Usage Between SMEs and MNCs or LLCs

The findings corroborated with Hwang's (2022) study, which is probably the closest study to this, on the challenges and strategies for the adoption of smart technologies in Singapore's construction industry, but adds to the understanding of the differences between Multi-national Companies (MNCs), Large Local Companies (LLCs) and SMES due to due to financial resources, expertise and risk appetite. Essentially, MNCs have strong financial backing, global expertise and compliance with global standards drives early adoption of smart technologies; LLCs tend to adopt smart technologies at a moderate pace, balancing cost and innovation, focus on local demand and align strategic investments with the Building and Construction Authority's initiatives such as Built Environment Transformation Fund to adopt smart or productive technologies such as Integrated Digital Delivery (IDD) and Prefabricated Prefinished Volumetric Construction (PPVC); whereas SMEs face resource constraints which limit adoption of cost-effective solutions in the long run, has a higher reliance on government support such as Productivity Solutions Grant and tend to gravitate to pragmatic adoption focusing on affordability and specific gains such as automation for labour efficiency.

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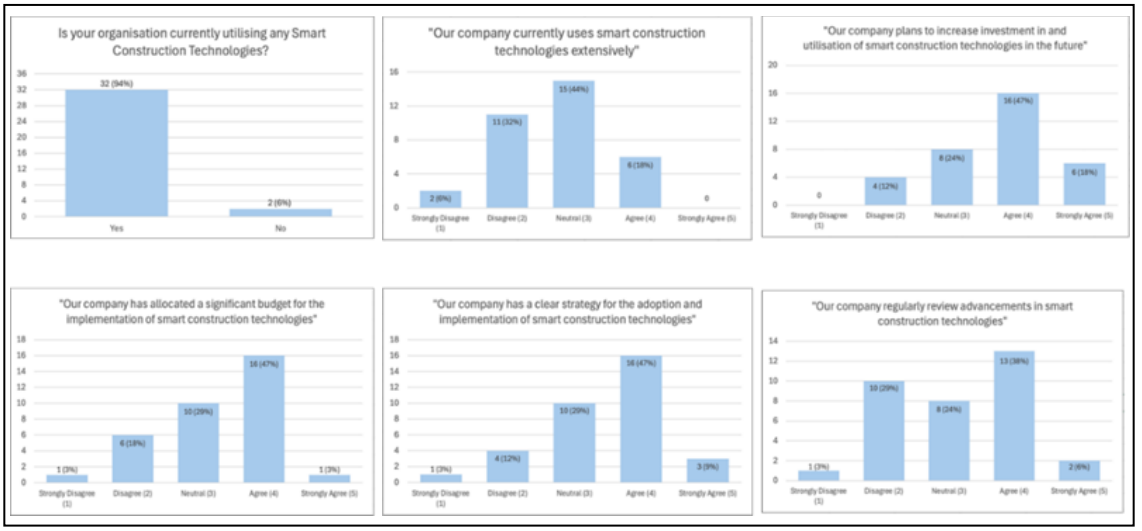

Clockwise from top-left: is your organisation currently utilising any SCT; our company currently uses SCT extensively; our company plans to increase investment and utilisation of SCT in the future; our company has allocated a significant budget for the implementation of SCT; our company has a clear strategy for the adoption and implementation of SCT; our company regularly reviews advancements in SCT.

Figure 1. Survey Findings on SCT Adoption by SMEs

Source: Authors (2024)

The Nature of the SMEs Does Not Significantly Impact the Adoption of SCT

The Chi-Squared test is a non-parametric method used to assess the relationship between categorical variables. Cramér's V, on the other hand, helps quantify the strength of this relationship. A Cramér's V value above 0.6 indicates a strong association, values between 0.2 and 0.6 suggest a moderate association and values below 0.2 indicate a weak association (Yelland, 2012). With a p-value of 0.251 for Chi-Squared Test and Cramér's V of 0.197, it is suggested that the nature of the organisation among SMEs does not significantly affect the adoption of SCT. This finding was contradictory to the expectation that the success of SCT adoption depends not only on technology but also on organisational readiness. It was thought that leadership commitment, open communication and a culture supportive of innovation and change management are critical. However, these were not teased out by the survey findings.

SMEs Do Exhibit a Strong Inclination Towards Adopting SCT

The preposition tested whether SMEs have a strong inclination to adopt SCT, with data collected through a questionnaire assessing their plans and intentions. Cronbach's Alpha showed good internal consistency (0.843), confirming the reliability of the survey tool. A normality test using the Shapiro-Wilk method revealed that the data were not normally distributed, leading to the use of a non-parametric one-sample Wilcoxon signed-rank test. The results indicated that SMEs are generally inclined to adopt SCT, particularly in areas such as financial investment, strategic planning and budget allocation, with three (3) out of four (4) key statements supporting this. However, a gap was identified in the consistent review of new technologies, suggesting SMEs are less proactive in evaluating emerging SCT solutions.

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Table 6. Interviewee's Perspectives on SMEs Circumstances

Interviewee Alias	Quote
Interviewee B	"…the challenge lies in having sufficient resources, budget and human talent to build a team… need to ensure both feasibility and practicality in any proposed solution."
Interviewee C	"… focus on keeping the business afloat, maximising cash flow and increasing profits… influences their motivation… to adopting frontier technologies that have yet to be proven and is unlikely to invest… unless it offers a clear business or proprietary advantage over competitors. MNCs often view technology implementation as a means of enhancing their brand and positioning themselves at the forefront of industry trends… they are more likely to be proactive in exploring and implementing the latest SCT."

Source: Authors (2024)

Alluding to this point, interviewees highlighted that SMEs face resource limitations and are focused on practical, proven technologies, which might explain the lack of continuous technological evaluation (Table 6). This focuses on survival and short-term feasibility over long-term innovation may hinder SMEs' ability to stay competitive and fully leverage the latest advancements in SCT, unlike larger companies that are more proactive in adopting cutting-edge technologies.

Drivers Do Significantly Enhance the Adoption of SCT by SMEs

To evaluate the preposition regarding the drivers influencing SCT adoption in SMEs, data were collected through the questionnaire and analysed using inferential statistics. Once more, Cronbach's Alpha (CA) reliability test yielded a coefficient of 0.863, indicating strong consistency for the survey tool. The normality test indicated that the data were not normally distributed, prompting the use of the one-sample Wilcoxon signed-rank test. The results indicated that all 15 drivers significantly influence SCT adoption, with top drivers related to cost savings, government grants and regulatory requirements. These drivers align with SMEs' primary challenges, including resource constraints and the need for financial incentives.

Table 7. Interviewees' Perspectives on Top 5 Drivers for SCT Adoption by SMEs

Interviewee Alias	Consensus	Quote
Interviewee A	All five (5) drivers are agreed upon as significant for SMEs.	<u>Significance for financial incentives and regulatory requirements</u> "They often lack the resources needed to implement such technologies. This includes financial resources to invest, the cost of training and developing staff, or recruiting people with the right expertise." "... The key initiatives that emerged were enforcing its use through contractual requirements and allocating funds and grants to support its adoption," "... only adopt these technologies when it is specified in their contracts or when government grants are available to offset the investment."
Interviewee B	All five (5) drivers are agreed upon as significant for SMEs. However, it is suggested that the significance of the top driver may vary.	<u>Opinion towards top driver</u> "While implementing new technology can make tasks more efficient and generally improve service quality, it can also lead to an increase in operational costs." <u>Significance for financial incentives</u> "Without government grants… organisations face significant challenges in moving forward with their implementation… adoption of smart technology does not always guarantee success,

		the high development and implementation costs … pose additional risks that must be considered." Significance for regulatory requirements "... many tenders now include an innovation category as part of the scoring system. To score well … we must incorporate the use of technology tailored to site conditions." Significance for improved performance "... this technology must be able to assist employees in their work… use it effectively to add value for clients or enhance the scope of work … the ability to generate data that can drive analytics and shape suitable strategies." "The bottom line is that the technology must provide tangible value to the organisation"
Interviewee C	All five (5) drivers are agreed upon as significant for SMEs.	Significance for regulatory requirements "... emphasis on smart and technological tool adoption has steadily increased in public sector projects… often a key evaluation criteria and/or consideration." Significance for improved performance and profit "… implementation.. is heavily dependent on the specific trade and motivation can vary… based on… contract value, project risks, scale of the business and profit margins... impact on productivity and costs will determine the degree of technology implementation." "... profit margins are always and will always remain a crucial factor in any form of implementation"

Source: Authors (2024)

Table 8. Interviewees' Perspectives on Bottom 3 Drivers for SCT Adoption by SMEs

Interviewee Alias	**Consensus**	**Quote**
Interviewee A	Two (2) of the three (3) drivers are agreed to have low significance for SMEs, while there is disagreement regarding the significance of the lowest-ranked driver.	Limited relevance of performance outcomes "... they are largely outside of their immediate context… in the aftermath of COVID-19, SMEs are primarily focused on survival … before considering growth and sustainability efforts involving the use of SCT." Significance of practical demonstrations "... hesitant to be first movers in the industry… learning from the experiences of others is perceived as a safer and more cost-effective approach… a lack of initiative within the industry, as the financial consequences of failure can be significant."
Interviewee B	All three (3) drivers are agreed to have low significance for SMEs.	Limited relevance of practical demonstrations "... can be rather superficial, as it may fail to address the complexities involved in implementing specific technologies tailored to an organisation's unique situation."
Interviewee C	All three (3) drivers are regarded as varying in significance, depending on the context.	Possible significance of performance outcomes "...largely depends on the target customers and the nature of the project. If clients are sustainability-focused and place a strong emphasis on sustainability standards… observed in both public and private projects… will serve as a significant driver for implementation."

Source: Authors (2024)

Table 9. Interviewees' Perspectives on Top 5 Barriers for SCT Adoption by SMEs

Interviewee Alias	Consensus	Quote
Interviewee A	All five (5) barriers are agreed upon as significant for SMEs.	Emphasis on SMEs' resources "While adopting SCT can be beneficial, it often involves significant financial costs that many SMEs are unable to afford." "They often lack the resources needed … includes financial resources to invest, the cost of training and developing staff, or recruiting people with the right expertise." "A common issue in the industry is the competition for talent … some companies … poach those trained employees once they have gained sufficient experience" Opinion towards practicality of SCT "... it is important to note that this issue affects everyone, including non-SMEs." "... use of innovative technology is intended to increase efficiency… users along the value chain might not be able to reap the full benefits due to their skill level… given the prominent presence of the older generation in the industry."
Interviewee B	All five (5) barriers are agreed upon as significant for SMEs.	Emphasis on SMEs' resources "... cost is very important… as long as the cost of the technology is reasonable and it proves to be a profitable investment for the business, I am sure people will adopt it." "... the challenge lies in having sufficient resources, budget and human talent to build a team for the adoption, implementation and development of the technology." "... a continuous need to improve technology development, as technology is constantly evolving. What was initially developed or implemented may not be comprehensive enough, necessitating ongoing enhancements… fail to deliver a return on investment… business sustainability… may be significantly impacted." Opinion towards practicality of SCT "... during the implementation… the process can either be streamlined or complicated, depending on the context, including the stakeholders involved and the specific site conditions."
Interviewee C	All five (5) barriers are agreed upon as significant for SMEs.	Emphasis on SMEs' resources "... highly sensitive to cash flow and profit margins… cost implications… related to purchasing and using SCT or hiring skilled workforce to operate… will significantly impact them." "... challenging for SMEs to hire specialists or compete for skilled labour, given the talent shortages and demand within the industry. … often require their workers to be multi-taskers."

Source: Authors (2024)

In terms of rankings, drivers under the regulative and normative pillars such as cost savings, government grants, and market competitiveness were rated highest, while drivers related to cultural-cognitive factors, such as adaptability and successful case studies, ranked lowest (Tables 7 and 8). Interviewees attested the significance of financial incentives and regulatory requirements, noting that SMEs often rely on government support to overcome financial barriers to adopting SCT. Conversely, drivers like practical demonstrations were seen as less important, as SMEs tend to prioritise immediate financial and performance benefits over long-term growth considerations. Overall, the findings suggest that SMEs are

more influenced by external pressures, such as financial incentives and regulatory compliance, than by internal cultural beliefs or shared knowledge about SCT.

Barriers do Significantly Reduce the Adoption of SCT by SMEs

The survey also seeks to identify key barriers to the adoption of SCT by SMEs. Again, the reliability of the data was confirmed through a Cronbach's Alpha of 0.835 and normality tests revealed that the data was not normally distributed, leading to the use of a non-parametric Wilcoxon signed-rank test. The results showed that all barriers significantly impact SCT adoption. The barriers were ranked, with those under the normative pillar, such as high investment costs, resource gaps, and integration challenges, being the most significant.

Table 10. Interviewees' Perspectives on Bottom 3 Barriers for SCT Adoption by SMEs

Interviewee Alias	Consensus	Quote
Interviewee A	All three (3) barriers are agreed to have low significance for SMEs.	Limited relevance of governing rules and standardised support for SCT "SMEs primarily engage in small, non-critical projects… do not need to utilise complex types of SCT that would require significant consideration of the aforementioned points." "... tasks typically do not involve sensitive information, thereby reducing concerns related to data security."
Interviewee B	Two (2) of the three (3) barriers are agreed to have low significance for SMEs, while there is varying significance of the second lowest-ranked driver.	Limited relevance of governing rules "Regarding the uncertainty surrounding legal aspects… there are always ways to navigate these issues and address any problems arising from the use… especially if you are committed to leveraging their benefits." Possible relevance of governing rules "... depends on the specific technology being adopted. If the data collected includes confidential information… protected under the Personal Data Protection Act… responsibility for cybersecurity and the long-term costs associated… would pose a significant barrier."
Interviewee C	All three (3) barriers are regarded as varying in significance, depending on the context.	Possible relevance of governing rules "... in relative terms, cost will always be more important than the mentioned factors… this may vary depending on the project's context and the client's requirements."

Source: Authors (2024)

In contrary to the drivers for adopting SCT by SMEs, whereby drivers under the regulative and normative pillars such as cost savings, government grants, and market competitiveness were rated highest, it was found that barriers under the normative pillar are more significant for local SMEs compared to those under the cultural-cognitive and regulative pillars. Interviewees highlighted the financial strain SMEs face in adopting SCT, including the difficulty in acquiring skilled labour and managing ongoing technology costs. Regulatory barriers such as legal uncertainties and compliance issues, were considered less significant, especially for SMEs working on smaller projects with less complex requirements.

The findings suggest that SMEs' primary hurdles in adopting SCT stem from financial constraints, skill shortages and the ongoing need to upgrade systems. Cultural-cognitive barriers, like resistance to change and lack of digital talent, also play a role. However, regulatory concerns were viewed as secondary, with SMEs prioritising operational efficiency and survival over compliance issues. Interviewees emphasised that

while regulatory factors matter, they are less pressing compared to the financial and resource-related challenges that SMEs face in adopting new technology (Tables 9 and 10).

Comparison of Findings with Previous Studies

Overall, the findings aligned strongly with prior international and Singapore-focused studies, reinforcing that SMEs' SCT adoption is primarily constrained by financial, resource, and capability limitations rather than lack of awareness or perceived usefulness. Consistent with Hwang et al. (2022) and Ofori et al. (2020), SMEs ranked financial constraints, competition with larger firms and skill shortages as dominant challenges, while regulatory compliance was secondary. This mirrors broader SME survival-focused behaviour reported by Gamage et al. (2020) and Prasanna et al. (2019), where short-term cash flow and risk mitigation outweigh long-term digital transformation.

The high reported SCT adoption rate but limited depth of use corroborates Autodesk and Deloitte (2024) and Chen et al. (2021), which observed that SMEs often adopt BIM, IoT, and cloud tools superficially without deep process integration. The concentration of extensive SCT use in architectural and engineering firms further supports Casini (2022) and Van der Heijden (2023), who identified BIM and cloud-based CDEs as foundational but unevenly embedded across Construction 4.0 maturity levels.

Drivers such as cost savings, government grants, and regulatory requirements align with Institutional Theory (Scott, 2014), echoing findings by Liao and Teo (2018) and Seyman-Guray and Kismet (2023) that regulative and normative pressures dominate early-stage adoption. Conversely, cultural-cognitive drivers ranked low, consistent with Parasuraman's (2000) and Chen et al.'s (2022) observations that organisational readiness in SMEs lags behind external mandates.

In summary, both quantitative and qualitative data converge on a clear picture: Singaporean SMEs recognise SCT benefits but are constrained by cost, resources and a cautious organisational culture. Drivers, especially government support and market pressures are necessary to tip the balance toward adoption. These insights suggest practical actions: financial grants, tax incentives, or subsidised loans could lower upfront cost barriers; targeted training programs can build SME workforce skills; and industry-led case studies or 'best practice' demos may reduce risk perceptions. Collaboration platforms linking SMEs with technology providers could also help share expertise, addressing the social aspect of change management. It is evident that there is strong alignment comparing these findings with existing literature: the challenges SMEs face mirror those in other countries, but the solutions must be locally tailored (e.g. Singapore's PPVC and Green Plan initiatives).

CONCLUSION

This study successfully addressed the six (6) key objectives related to the adoption of SCT by SMEs in Singapore. Firstly, it emphasised SMEs' critical role in the construction industry, particularly in supporting larger firms with specialised services, while also identifying unique challenges such as intense competition and financial constraints, exacerbated by the COVID-19 pandemic. Secondly, it provided a comprehensive understanding of SCT, highlighting the significant advantages of digital technologies such as BIM, IoT, AI, and robotics over traditional construction methods.

The study also explored the relationship between the characteristics of SMEs and their adoption of SCT, revealing that organisational traits did not significantly influence adoption rates. Additionally, while there is a positive outlook for SCT adoption among SMEs, the study found that adoption trends are driven

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primarily by perceived benefits, rather than a broad commitment to advanced technology usage. The identification of 15 drivers and 13 barriers to SCT adoption further revealed that drivers are largely associated with regulatory and normative influences, while barriers are predominantly shaped by industry norms and financial constraints. Interview data emphasised that financial strain and workforce challenges are SME-critical hurdles, whereas regulatory/legal issues are secondary for most SMEs.

Based on these findings, this study recommends the following strategies: provide targeted financial support (grants, loans, subsidies) for SMEs' SCT investments; offer accessible training and technical assistance to build ICT skills; encourage peer learning and best-practice networks so SMEs can learn from successful implementations; and ensure government procurement policies continue to include SCT criteria (to create demand). These measures address the identified barriers directly and leverage the strongest drivers.

Finally, this study admittedly has its limitations: the modest sample size (34 SMEs) and short data collection window may affect generalisability. Future research could use larger samples or longitudinal designs to track adoption over time. Nevertheless, this study makes a significant contribution by providing empirical evidence on SME-specific adoption factors and practical insights to accelerate SCT diffusion in the construction sector.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Rynn Ho Shi Ying carried out the research and drafted the report; Luke Peh Lu Chang wrote the journal paper, corresponded with the editors and revised the manuscript; Low Sui Pheng anchored the review and approved the article submission.

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