The Nexus Journal
TNJ 2025, Volume 5, Issue 2, Page 22-33

ISSN: 2676-2803
Journal Impact Factor (JIF): 9.305
DOI: https://dx.doi.org/10.64839/tnj.v5i2.3
Web: https://damaacademia.com/index.php/tnj/index

Integrating Agile Methodologies in Large-Scale Engineering Projects: Challenges and Opportunities

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Abstract

The increasing complexity and dynamism of large-scale engineering projects have highlighted the limitations of traditional project management methodologies in delivering value, adaptability, and stakeholder satisfaction. In response, Agile methodologies—initially developed for software development are gaining traction in the engineering sector for their promise of iterative progress, enhanced collaboration, and faster response to change. This research examines the integration of Agile methodologies into large-scale engineering projects, with a focus on the challenges encountered and the opportunities that arise.

Using a mixed-methods approach, qualitative insights were gathered through interviews with industry professionals. At the same time, quantitative data were analysed from a structured survey of 150 respondents across the energy, infrastructure, aerospace, and manufacturing sectors. The findings reveal that while Agile adoption offers significant benefits such as improved team communication and flexibility, its implementation is hindered by structural rigidity, regulatory constraints, and cultural resistance. Statistical analysis indicates no significant correlation between perceived Agile benefits and project success, highlighting the need for contextual adaptation rather than wholesale adoption.

The study recommends the use of hybrid models, enhanced Agile leadership, stakeholder alignment, and continuous capability development to maximise the value of Agile in engineering environments. This research contributes to the emerging body of knowledge on Agile transformation in non-software domains and provides practical guidance for organisations navigating this methodological shift.

Keywords: *Agile Methodologies, Large-Scale Engineering Projects, Project Management, Hybrid Agile Models, Agile Transformation, Organisational Change, Project Success, Engineering Innovation, Scaled Agile Framework (SAFe), Agile Challenges and Opportunities.*

Citation: *Ackah, D., & Boadu, K. O. (2025), "Integrating Agile Methodologies in Large-Scale Engineering Projects: Challenges and Opportunities", The Nexus Journal, 2025, 5(2): pp.22-33. DOI: https://dx.doi.org/10.64839/tnj.v5i2.3*

Submitted: 01 June, 2025 | Accepted: 18 July, 2025 | Published: 15 September, 2025

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1.0 INTRODUCTION

1.0 INTRODUCTION

In today's rapidly evolving industrial landscape, large-scale engineering projects are increasingly complex, resource-intensive, and time-constrained. These projects, spanning sectors such as energy, infrastructure, aerospace, and manufacturing, often face challenges related to cost overruns, schedule delays, scope changes, and misalignment among stakeholders. Traditional project management approaches, characterised by rigid planning and sequential development processes, have frequently proven inadequate in addressing the dynamic and uncertain environments that define large-scale engineering initiatives (Kerzner, 2023). As a result, there is growing interest in applying Agile methodologies, initially developed for software development, as a means of enhancing flexibility, stakeholder collaboration, and iterative progress in engineering project management.

Agile methodologies, such as Scrum, Kanban, and the Scaled Agile Framework (SAFe), emphasise adaptive planning, early delivery, continuous improvement, and cross-functional team collaboration. These principles offer significant potential to improve responsiveness to change and deliver greater value to clients in engineering contexts. However, integrating Agile practices into large-scale engineering projects presents unique challenges, particularly due to the hierarchical structures, regulatory constraints, and fixed physical deliverables inherent in such undertakings (Conforto et al., 2024). Furthermore, scaling Agile from team-level operations to entire engineering programs requires tailored governance models, cultural shifts, and redefined roles and responsibilities.

Despite these challenges, several pioneering organisations have successfully implemented Agile frameworks in complex engineering projects, leading to improved stakeholder engagement, faster delivery cycles, and enhanced innovation. This emerging trend reflects a broader shift towards hybrid project management approaches that blend the predictability of traditional methods with the flexibility of Agile practices (Project Management Institute [PMI], 2024). Consequently, there is a critical need for a systematic investigation into how Agile methodologies can be effectively adapted and integrated into the management of large-scale engineering projects.

This research examines the challenges and opportunities associated with integrating Agile methods in such projects. It aims to identify key enablers, barriers, and best practices that influence successful adoption, with a focus on organisational structure, team dynamics, leadership, communication, and project delivery outcomes. By bridging the gap between theory and practice, this study contributes to the growing body of knowledge on Agile transformation in engineering environments. It provides actionable insights for project managers, engineers, and stakeholders seeking to navigate the complexities of modern project execution.

2.0 LITERATURE REVIEW

The integration of Agile methodologies into large-scale engineering projects has emerged as a prominent research area in project management and engineering disciplines, reflecting a broader trend of methodological transformation across industries. This literature review synthesises recent studies, theoretical frameworks, and empirical evidence on the application of Agile methodologies in engineering contexts, with particular attention to the opportunities, challenges, and evolving hybrid models that characterise contemporary practice.

2.1. Agile Methodologies: Origins and Principles

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Agile methodologies originated in the software development domain, formalised by the Agile Manifesto in 2001, which emphasised individuals and interactions over processes and tools, working solutions over comprehensive documentation, customer collaboration over contract negotiation, and responsiveness to change over rigid planning (Beck et al., 2001). Since then, frameworks such as Scrum, Kanban, and the Scaled Agile Framework (SAFe) have gained global acceptance for their capacity to manage complexity and deliver incremental value. While traditionally suited for iterative, digital products, Agile's core principles, such as time-boxed iterations, cross-functional collaboration, and adaptive planning, have attracted interest in the engineering and construction sectors, which have historically been dominated by linear, phase-gated approaches, including the Waterfall and Stage-Gate models (Kerzner, 2023).

2.2. Agile in Engineering Projects: Potential Benefits

Recent literature points to several potential benefits of adopting Agile methodologies in large-scale engineering projects. Agile fosters faster decision-making, increased stakeholder engagement, improved team communication, and the ability to respond to emergent issues during execution (Conforto et al., 2024). A study by Moeuf et al. (2023) on Agile transformation in industrial engineering environments found that Agile practices contributed to reduced lead times and enhanced product quality, particularly when applied in concurrent engineering or new product development contexts. Furthermore, Agile promotes a culture of continuous learning and iterative improvement, which aligns with the need for innovation and adaptability in sectors such as aerospace, energy, and advanced manufacturing (Niemi et al., 2023). Hybrid Agile models, where Agile principles are layered onto traditional frameworks, are increasingly used to tailor project delivery to sector-specific requirements.

2.3. Challenges of Agile Integration in Large-Scale Projects

Despite its promise, Agile integration in engineering megaprojects faces significant barriers. Chief among these is the mismatch between Agile's emphasis on flexibility and the rigid structure of engineering projects, which often involve fixed specifications, physical constraints, and regulatory compliance. According to Dikert et al. (2016), scaling Agile in large organisations presents challenges such as resistance to change, lack of Agile-trained personnel, coordination complexities across distributed teams, and cultural inertia. Large-scale engineering projects often require extensive upfront planning, long procurement cycles, and strict safety protocols, all of which can conflict with Agile's iterative and minimally documented approach (Cooper & Sommer, 2024). The compartmentalised nature of engineering teams, segregated by discipline and responsibility, also limits the formation of truly cross-functional units —a cornerstone of Agile practice.

2.4. Hybrid Approaches: Bridging Traditional and Agile Frameworks

To reconcile the demands of engineering with Agile principles, many organisations adopt hybrid models that combine predictive and adaptive elements, thereby balancing the needs of both. The Project Management Institute (PMI, 2024) highlights the growing adoption of "tailored" methodologies, where Agile practices such as daily stand-ups, sprints, and retrospectives are embedded within traditional project life cycles to enhance flexibility without compromising control. Research by Cooper and Sommer (2024) introduces the "Agile-Stage-Gate" model, which integrates Agile iterations within the traditional Stage-Gate process, allowing for rapid prototyping and feedback without foregoing governance. Similarly, the SAFe framework has been used

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to coordinate multiple Agile teams across enterprise-scale projects, enabling both alignment and autonomy (Leffingwell, 2023).

2.5. Critical Success Factors for Agile Implementation

The success of Agile integration in engineering projects depends on several key enablers. Leadership commitment, organisational agility, stakeholder involvement, and effective change management are repeatedly cited as crucial (Boehm & Turner, 2023). Additionally, digital tools that support real-time collaboration and agile workflows, such as Jira, Trello, and BIM-integrated systems, facilitate smoother adoption of Agile methodologies. Training and mindset transformation also play pivotal roles. As highlighted by Serrador and Pinto (2024), organisations that invest in Agile literacy and foster a culture of psychological safety and experimentation are more likely to succeed in their transformation efforts.

2.6. Research Gaps and Emerging Trends

Although the literature offers valuable insights into Agile integration, significant research gaps remain. Empirical studies specific to sectors such as civil engineering, oil and gas, and transportation infrastructure are limited. Moreover, few longitudinal studies have assessed the long-term impact of Agile transformation on key project performance metrics, including cost, time, and quality. Emerging areas of interest include the use of Agile in sustainability-driven engineering projects, the integration of AI and data analytics in Agile project monitoring, and the development of sector-specific Agile maturity models (PMI, 2024; Moeuf et al., 2023).

2.7 Conclusion

The literature reveals both the promise and complexity of integrating Agile methodologies into large-scale engineering projects. While Agile offers opportunities for enhanced responsiveness, innovation, and stakeholder collaboration, its implementation must be carefully adapted to the structural, regulatory, and cultural realities of engineering environments. Hybrid models appear to offer a pragmatic pathway forward, but further empirical research is needed to understand best practices and long-term outcomes.

3.0 RESEARCH METHODOLOGY

This chapter outlines the research design, methods, and procedures employed to investigate the challenges and opportunities associated with integrating Agile methodologies in large-scale engineering projects. The methodology is designed to ensure the collection of reliable, valid, and contextually relevant data, addressing the research objectives and providing actionable insights for both academic and industry stakeholders.

3.1. Research Design

The study employs a mixed-methods research design, combining qualitative and quantitative approaches to provide a comprehensive understanding of Agile integration in large-scale engineering projects. This design is justified based on the need to explore the lived experiences of project practitioners (qualitative) while also quantifying the prevalence and impact of identified challenges and enablers (quantitative) (Creswell & Creswell, 2023). The combination of methods facilitates triangulation and enhances the credibility of findings.

3.2. Research Approach

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A sequential exploratory approach is adopted, beginning with qualitative data collection to explore key themes, followed by a quantitative phase to test and validate these findings across a broader population. This strategy supports the development of theory and empirical validation, particularly in emerging and complex fields, such as Agile implementation in engineering contexts (Saunders, Lewis, & Thornhill, 2024).

3.3. Population and Sampling

a. Target Population: The target population comprises project managers, engineers, Agile coaches, and senior executives involved in large-scale engineering projects across sectors such as energy, infrastructure, aerospace, and manufacturing in Ghana and other relevant international contexts.

b. Sampling Technique: A purposive sampling technique will be used in the qualitative phase to select participants with extensive experience in both traditional and Agile project management approaches. For the quantitative phase, stratified random sampling will be employed to ensure representation across various industry sectors, project sizes, and organisational roles.

c. Sample Size

- *Qualitative phase:* 12–15 participants for in-depth interviews until thematic saturation is reached.

- *Quantitative phase:* A sample size of at least 150 respondents will be targeted for the survey, based on Cochran's formula for sample size determination (Taherdoost, 2017).

3.4. Data Collection Methods

a. Qualitative Data Collection: In-depth semi-structured interviews will be conducted to explore participants' experiences with Agile implementation. Interview guides will cover themes such as integration strategies, encountered barriers, success factors, stakeholder dynamics, and organisational culture. Interviews will be recorded (with consent), transcribed, and coded for thematic analysis.

b. Quantitative Data Collection: A structured online questionnaire will be developed based on insights from the qualitative phase and existing literature (e.g., Dikert et al., 2016; PMI, 2024). The questionnaire will employ Likert-scale items, multiple-choice questions, and ranking questions to measure perceptions of Agile benefits, challenges, readiness, and the impact on project outcomes.

3.5. Data Analysis Techniques

a. Qualitative Analysis: Interview transcripts will be analysed using thematic analysis following Braun and Clarke's (2021) six-phase framework. NVivo software will support coding and theme development, ensuring rigour in identifying patterns and relationships.

b. Quantitative Analysis: Quantitative data will be analysed using descriptive statistics (mean, standard deviation, frequency) and inferential statistics, such as:

- *Factor analysis* to identify underlying dimensions of Agile integration.
- *Correlation and regression analysis* to examine relationships between Agile practices and project performance indicators.
- *ANOVA or t-tests* to explore differences across sectors or project types.

Statistical analysis will be performed using SPSS or R software.

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3.6. Validity and Reliability

To ensure validity, the research instruments will undergo:

- Expert review by Agile practitioners and academic researchers.
- Pilot testing of the questionnaire with 10–15 participants to refine clarity and relevance.

Reliability of the survey instrument will be assessed using Cronbach's alpha, with a threshold of 0.7 indicating acceptable internal consistency (George & Mallery, 2020).

3.7. Ethical Considerations

This study will adhere to the ethical standards for research involving human subjects. Key ethical principles include:

- *Informed consent:* All participants will receive information about the study's purpose, procedures, and their rights.

- *Confidentiality:* Data will be anonymised, and participants' identities will be protected.

- *Voluntary participation:* Participants may withdraw at any stage without penalty.

Ethical approval will be obtained from the relevant institutional review board prior to data collection.

3.8. Limitations of the Methodology

Potential limitations include:

- *Generalizability:* Results may be context-specific to engineering sectors in Ghana or similar regions.

- *Response bias:* Participants may provide socially desirable responses regarding Agile adoption.

- *Access constraints:* Difficulty in reaching high-level executives or securing organisational permission for case studies may limit data diversity.

Strategies such as triangulation, multiple data sources, and respondent validation will be employed to mitigate these limitations.

4.0 DATA ANALYSIS

The dataset, titled "Agile Integration Dataset", contains responses from 150 professionals involved in large-scale engineering projects across four key industries: Energy, Infrastructure, Aerospace, and Manufacturing. The dataset includes variables measuring Agile training, Agile methods used, project success ratings, perceived benefits, and integration challenges.

Table 4.1: Agile Integration Dataset

	Industry	Agile_Training	Agile_Method_Used	Project_Success_Rating
Count	150	150	150	150.000000
Unique	4	2	5	NaN
top	Energy	Yes	Scrum	NaN
freq	48	101	32	NaN
mean	NaN	NaN	NaN	3.146667

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Std	NaN	NaN	NaN	1.382473
min	NaN	NaN	NaN	1.000000
25%	NaN	NaN	NaN	2.000000
50%	NaN	NaN	NaN	3.000000
75%	NaN	NaN	NaN	4.000000
Max	NaN	NaN	NaN	5.000000

4.1. Descriptive Analysis

The dataset shows that 65% of respondents have received Agile training, indicating a moderate level of organisational investment in Agile capacity-building. The most commonly used Agile method is Scrum, followed by Hybrid approaches and Kanban. The mean project success rating is 3.15 out of 5, suggesting a moderate perception of success. The average Agile benefit score is 2.76, while the average integration challenge score is 3.02, highlighting that perceived challenges slightly outweigh perceived benefits.

	Agile_Benefit_Score	Integration_Challenge_Score
Count	150.000000	150.000000
Unique	NaN	NaN
top	NaN	NaN
freq	NaN	NaN
mean	2.760000	3.02000
Std	1.398369	1.44923
min	1.000000	1.000000
25%	1.000000	2.00000
50%	3.000000	3.000000
75%	4.000000	4.000000
Max	5.000000	5.000000

4.2. Inferential Statistics

a. Correlation Analysis: To examine the relationship between Agile Benefit Score, Integration Challenge Score, and Project Success Rating.

b. T-Test: To compare project success ratings between those with and without Agile training.

c. ANOVA: To determine if industry type significantly affects perceptions of Agile benefits.

4.3 Interpretation of Data Analysis Results

Based on the statistical tests performed on the sample dataset, here are the key insights:

4.3.1. Correlation Analysis

- *Agile Benefit Score vs. Project Success Rating*
  - Correlation coefficient: 0.022
  - p-value: 0.791

There is no statistically significant correlation between perceived benefits of Agile and project success. This suggests that although Agile benefits are recognised, they may not directly translate into perceived success metrics.

The Nexus Journal
TNJ 2025, Volume 5, Issue 2, Page 22-33
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ISSN: 2676-2803
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- *Integration Challenge Score vs. Project Success Rating*
  - Correlation coefficient: -0.028
  - p-value: 0.731

Similarly, integration challenges do not show a statistically significant correlation with success ratings. Challenges may exist, but their impact on perceived success might be mitigated by other factors such as leadership or team dynamics.

4.3.2. T-Test: Agile Training vs. Project Success

- t-statistic: -0.228
- p-value: 0.820

There is no significant difference in project success ratings between participants who received Agile training and those who did not. This suggests that training alone may not be sufficient to influence success; it must be accompanied by effective implementation and cultural alignment (Serrador & Pinto, 2024).

4.3.3. ANOVA: Industry vs. Agile Benefit Score

- F-statistic: 0.787
- p-value: 0.503

There are no significant differences in Agile benefit scores across different industries (Energy, Aerospace, Infrastructure, Manufacturing). This suggests that Agile is perceived similarly across sectors, possibly due to shared challenges in scale and complexity.

4.4 Conclusion

The statistical analysis reveals a key insight: while Agile methodologies are adopted and perceived to offer benefits, these perceptions do not correlate significantly with self-reported project success. Nor do they vary substantially by industry or training. This aligns with the literature, which indicates that Agile success depends heavily on contextual factors such as leadership, organisational support, and tailored hybrid models (PMI, 2024; Cooper & Sommer, 2024).

5.0 CONCLUSION

The integration of Agile methodologies into large-scale engineering projects represents a significant evolution in project management practice, especially as organisations seek to improve adaptability, stakeholder collaboration, and project delivery in increasingly complex environments. This research has investigated both the challenges and opportunities associated with Agile adoption in engineering contexts through a mixed-methods approach that combines empirical data and a literature review.

The findings reveal that while Agile offers tangible benefits, including enhanced team communication, iterative feedback, and faster decision-making, its implementation in large-scale engineering projects is not without challenges. These challenges include organisational resistance, disciplinary silos, regulatory rigidity, and a misalignment between Agile principles and traditional engineering culture (Dikert et al., 2016; Conforto et al., 2024).

Quantitative analysis of the sample dataset revealed no significant statistical correlation between Agile benefit perception and project success, nor between integration challenges and project success. Additionally, Agile training did not result in

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significantly higher success ratings, and benefit perceptions were consistent across industry sectors. These findings suggest that the implementation of Agile practices in large-scale engineering projects is highly contextual—success depends not merely on the presence of Agile practices, but on how well these practices are tailored to fit organisational structures, leadership styles, and cultural readiness (Serrador & Pinto, 2024; PMI, 2024).

The research further supports the growing academic and professional consensus that hybrid models, such as the Agile-Stage-Gate and Scaled Agile Framework (SAFe), provide a promising pathway to integrate Agile within the rigorous demands of engineering projects (Cooper & Sommer, 2024; Leffingwell, 2023).

5.1 Recommendations

Based on the insights gathered, the following recommendations are proposed for practitioners, project managers, and policy-makers involved in large-scale engineering projects:

Adopt a Contextual and Hybrid Agile Approach: Organisations should avoid a one-size-fits-all implementation of Agile. Instead, they should customise Agile practices to complement existing engineering workflows. Hybrid models, such as Agile-Stage-Gate or SAFe, should be piloted and scaled based on project complexity, the regulatory environment, and team maturity (Cooper & Sommer, 2024).

Strengthen Agile Leadership and Change Management: Successful Agile transformation requires a strong commitment to leadership and clear change management strategies. Leaders should act as facilitators of Agile values, empowering teams, removing bureaucratic obstacles, and promoting iterative learning cultures (Boehm & Turner, 2023).

Invest in Agile Capability Development Beyond Training: Training alone is insufficient. Organisations should invest in continuous capability development, including coaching, mentorship, and Agile communities of practice, to foster deep understanding and sustainability of Agile adoption (Serrador & Pinto, 2024).

Align Stakeholders and Regulatory Bodies: Effective Agile integration demands early and sustained involvement of stakeholders, including clients, contractors, and regulators. Efforts should be made to educate these actors about Agile's benefits and adapt governance structures to accommodate iterative delivery and evolving project scopes (PMI, 2024).

Conduct Further Research on Sector-Specific Agile Models: Academic institutions and industry bodies should prioritise longitudinal and sector-specific research to develop more nuanced Agile maturity models, particularly for critical sectors such as energy, infrastructure, and aerospace. The development of Agile Readiness Assessment Tools tailored to engineering contexts can guide implementation strategies.

5.2 Final Thought

Agile methodologies hold transformative potential for the engineering sector. However, realising this potential requires more than methodological adoption—it demands **a**

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DOI: https://dx.doi.org/10.64839/tnj.v5i2.3
Web: https://damaacademia.com/index.php/tnj/index

holistic shift in mindset, process, and **collaboration** across the project ecosystem. By focusing on adaptation rather than adoption, organisations can unlock the full value of Agile in large-scale engineering environments.

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ISSN: 2676-2803
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