

Conceptual Maturity Framework for Digital Twin Technology Adoption and Scaling

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Abstract: A Digital Twin is a dynamic virtual representation of a physical entity that mirrors its real-world counterpart through continuous, bi-directional data exchange. It promises to transform how organisations design, monitor, and improve complex systems, yet adoption remains uneven. Although use-cases have spread across smart cities, manufacturing, healthcare, energy, transportation, and supply chains, most implementations stay confined to a single site or use-case, and many never move beyond the pilot stage. Existing digital maturity models describe progress as a single linear staircase. This approach does not fit Digital Twin technology, which behaves as both an intelligent environment and a complex adaptive system. The literature therefore lacks a maturity model that connects early adoption to enterprise-wide and cross-organisational scaling, and it rarely treats the two as separate problems. This paper proposes the Digital Twin Adoption-and-Scaling Maturity (DT-ASM) Framework, which conceptualises implementation as two interrelated but fundamentally different capability-building journeys. The Adoption Maturity ladder describes progression at the use-case level, from awareness through pilot selection, deployment and operational integration to routinised use. The Scaling Maturity ladder describes how the same organisation, with its ecosystem, moves from a single use-case through multi-asset replication, cross-domain federation, and ecosystem orchestration to a self-evolving industrial ecosystem. Four cross-cutting determinants shape both journeys: risk exposure, resource allocation cycles, ecosystem maturity, and organisational alignment. The framework is expressed as seven testable propositions with an operationalisation strategy providing a foundation for empirical validation and actionable guidance for industry leaders seeking a roadmap from experimentation to scalable deployment.

Keywords: Digital Twin, Technology Adoption, Technology Scaling, Maturity Model, Innovation

1. Introduction

A Digital Twin comprises a physical entity, its virtual counterpart, and the bidirectional data connections that synchronise the two, so that the digital model reflects the real-world state in near real time (Grieves and Vickers, 2017; Jones et al., 2020; Sharma et al., 2022). The concept was articulated by Michael Grieves in the early 2000s within the context of product life-cycle management and popularised through NASA's high-fidelity virtual models to mirror spacecraft conditions and rehearse missions before flight (Grieves, 2025; Jones et al., 2020). This continuous loop, or twinning, is what distinguishes a Digital Twin from conventional simulation with fixed inputs (Jones et al., 2020). Its value lies in allowing engineers and decision-makers to test ideas, predict failures, and optimise performance virtually before acting physically, cutting cost, shortening development cycles, and averting harm from unforeseen failures (Sharma et al., 2022). These capabilities have driven uptake across aerospace, manufacturing, healthcare, smart cities, and supply chains (Grieves, 2025; Richter, Campbell and Riedl, 2025).

Despite this momentum, full enterprise-wide deployment has not been achieved. Unlike mass technologies adopted on perceived usefulness and ease of use (Davis, 1989; Venkatesh et al., 2003), Digital Twin adoption stalls at the pilot stage for structural reasons: there is no agreed reference architecture and standards remain scarce (Sharma et al., 2022); every twin is domain-dependent and requires bespoke modelling, dedicated sensors, and continuous integration; and most applications sit at low readiness levels, constrained by limited organisational readiness, unclear benefit-cost cases, and regulatory ambiguity (Jones et al., 2020; Richter, Campbell and Riedl, 2025).

A Digital Twin is best understood as both an intelligent environment and a complex adaptive system. As an intelligent environment it relies on sensors, the Internet of Things (IoT), edge and cloud processing, and machine learning to sense, interpret, and support decisions in real time (Augusto et al., 2013). As a complex adaptive system it is a network of interconnected sub-systems that continuously exchange data and adjust to one another, each acting autonomously while sharing information with the rest (Haggall, Ahituv and Naveh, 2019). This dual nature is what makes Digital Twins both promising and challenging to scale.

This paper synthesises a maturity framework that organisations can use to map their current state and to chart a path toward scaling, reframing the strategic question from how sophisticated a twin is to how an organisation

converts adoption into scaling and captures value across its ecosystem. Maturity models translate abstract transformation goals into sequential stages, helping decision-makers assess capability and set targets (Haryanti, Rakhmawati and Subriadi, 2023; Senna et al., 2023), and they address the need for clearer pathways from pilots to institutional uptake (Richter, Campbell and Riedl, 2025). The central argument is that a single maturity axis conflates two capability journeys, adoption and scaling, whose risk profiles, time horizons, and ecosystem dependencies differ sharply. The Digital Twin Adoption-and-Scaling Maturity (DT-ASM) framework is developed to be empirically testable, positioned within three integrated theoretical lenses and against existing models, along with its matrix, determinants, and propositions.

2. Research Methodology

This research combines literature review with thematic synthesis and framework construction. This approach is suitable because Digital Twin empirical work is fragmented across disciplines, multiple theoretical lenses already exist, and many organisations succeed at pilots but stall at scale (Plekhanov, Franke and Netland, 2023; Senna et al., 2023). The paper is deliberately conceptual as it builds and positions a framework and derives testable propositions as a basis for empirical validation.

The search proceeded in two steps. First, scoping queries were run in Scopus (2010-2025) to map how the adoption and scaling literatures relate. They returned 56,540 records addressing technology adoption without any scaling terminology and 82,062 addressing scaling without any adoption terminology, but only 249 indexing both; restricted to the Digital Twin, 234 records paired the twin with adoption terms only, 150 with scaling terms only, a single record indexed both, and only 13 connected either to maturity. These counts confirmed that the two literatures run largely in parallel and shaped the master search string, which paired a Digital Twin block with a block of adoption-related and scaling-related terms, for example “technology adoption”, “technology acceptance”, “innovation adoption”, “scaling up”, “technology rollout”, “enterprise-wide implementation”, and “pilot to production”. The search string was also run in IEEE Xplore and the ACM Digital Library, chosen because the topic sits between management and digitalisation technology, and supplemented with backward and forward snowballing, which also retained foundational earlier works on the Digital Twin concept and the classical adoption and assimilation theories together with authoritative grey literature.

The searches identified 559 records: 385 from Scopus, 135 from IEEE Xplore, 12 from the ACM Digital Library, and 27 through snowballing. After removal of duplicates, titles and abstracts were screened and the remaining full texts were assessed against predefined inclusion and exclusion criteria. Studies were included when they defined or characterised the Digital Twin or examined the adoption, acceptance, scaling or maturity of the technology in an organisational setting. Reports were excluded when they addressed a non-industrial Digital Twin domain without theory-building intent, when they fell below the quality and relevance appraisal, or when the full text could not be retrieved. This yielded a focused corpus of 165 substantive records, each coded for theoretical lens, sector, unit of analysis, maturity stages, enablers and barriers, and the treatment of adoption versus scaling.

Coded extracts were grouped into five themes: the conceptual evolution of the Digital Twin; capability-based maturity models; classical adoption and acceptance theory; organisational assimilation; and industry deployment evidence. The synthesis showed that a single maturity axis conflates two capability journeys, a finding translated into the conceptual framework architecture of the Digital Twin Adoption-and-Scaling Maturity (DT-ASM), consisting of two five-stage ladders coupled by four cross-cutting determinants.

3. Literature Review

Across the focused corpus, the evidence indicates that the Digital Twin has now entered a phase of development in which adoption is expanding across smart cities, smart manufacturing, individually tailored healthcare, transportation, energy, and supply chains, supported by cloud-based Digital Twin platforms and increasingly sophisticated digital models (Sharma et al., 2022; Grieves, 2025). Industry leaders are using Digital Twins for production monitoring, medical-equipment diagnostics, port operations, and power-grid management (Sharma et al., 2022). A systematic review of Digital Twin publications found that the most frequently cited benefits include what-if scenario simulations, physical-twin performance optimisation, real-time monitoring, and improved decision-making (Richter, Campbell and Riedl, 2025). Despite this momentum, full enterprise-wide deployment has not yet been achieved: most implementations remain limited in scope, are confined to a single use-case or a single site, and many initiatives stay at the pilot or proof-of-concept stage.

3.1 Adoption, Assimilation, and Scaling

The innovation literature separates three related but distinct concepts. Technology adoption is the decision and first act of taking up a technology, shaped by perceived usefulness, ease of use, social influence, and facilitating conditions (Davis, 1989; Venkatesh et al., 2003; Dwivedi et al., 2019); in firms it typically takes the form of pilots driven by champions and gatekeepers (Roberts et al., 2021). Technology assimilation is the deeper process that follows adoption: the embedding of the technology into everyday routines, structures, skills, and culture. Zhu, Kraemer and Xu (2006) describe assimilation as three stages: initiation, adoption, and routinisation, and show that different factors matter at different stages, so the conditions that help a firm begin using a technology are not those that help it spread. Liang et al. (2007) find that institutional pressures drive assimilation mainly through the mediating role of top management, and Hasgall, Ahituv and Naveh (2019) show that organisations behaving as complex adaptive systems assimilate innovation more readily when structure is decentralised. Technology scaling is the broader expansion of an assimilated technology from local to widespread, cross-functional, and often cross-organisational use, which for Digital Twins depends on shared standards and regulation rather than isolated pilots (Sharma et al., 2022).

These concepts are frequently collapsed in practice. Much of the Digital Twin literature treats adoption as a single event and presents scaling as more of the same, obscuring that the two are governed by different logics: adoption is a decision at the use-case level under bounded risk, whereas scaling is an ecosystem-level achievement contingent on conditions the organisation does not fully control. The assimilation literature is the key to separating them, yet its stage logic has rarely been built into a Digital Twin maturity model.

3.2 An Integrative Theoretical Foundation

Because Digital Twin deployment spans organisational decision-making, individual acceptance, and ecosystem dynamics, no single theory explains it. The framework therefore integrates three complementary lenses. The technology-organisation-environment (TOE) framework (Tornatzky and Fleischer, 1990) organises the firm-level and contextual conditions of adoption into technology, organisation, and environment; it grounds the four cross-cutting determinants and suits a setting where progress depends on data governance, infrastructure investment, operating-model change, and risk governance rather than individual preference (Senna et al., 2023). The unified theory of acceptance and use of technology (UTAUT) supplies the individual-level micro-foundations that become decisive once end-users encounter a working twin, through performance expectancy, effort expectancy, social influence, and facilitating conditions (Venkatesh et al., 2003; Dwivedi et al., 2019); UTAUT is preferred over the technology acceptance model because its constructs subsume perceived usefulness and ease of use while better reflecting enterprise realities (Davis, 1989). The organisational assimilation perspective supplies the temporal logic of initiation, adoption, and routinisation, and the complex adaptive systems view that connects adoption to scaling (Zhu, Kraemer and Xu, 2006; Liang et al., 2007; Hasgall, Ahituv and Naveh, 2019). Combining the three yields an account that is organisational without ignoring users, and dynamic rather than static: TOE frames the conditions, UTAUT the acceptance, and assimilation the progression.

3.3 Existing Maturity Models and Their Limits

Across the focused corpus of previous research, three limitations recur in the maturity models most often used to describe technology progress. First, adoption models such as UTAUT measure individual perceptions well but stop at the point of decision, with limited elaboration on how readiness emerges across interacting sub-systems and organisational boundaries (Hasgall, Ahituv and Naveh, 2019). Second, stage-based maturity models: the acatech Industrie 4.0 Maturity Index (Schuh et al., 2017), the TOE-based Industry 4.0 model (Senna et al., 2023), the Extended Digital Maturity Model (Haryanti, Rakhmawati and Subriadi, 2023), the CITYSTEPS city-twin model (Haraguchi, Funahashi and Biljecki, 2024), and the capability-based model of Liu et al. (2024) describe progress as a single linear staircase. Linearity suits a standardised infrastructure such as a 5G mobile network, whose diffusion follows a log-normal saturation curve (Hutajulu, Dhewanto and Prasetyo, 2021), but fits a Digital Twin poorly, since the twin behaves as a complex adaptive system whose deployment is non-linear and emergent (Jones et al., 2020; Grieves, 2025). Third, the assimilation literature separates the determinants of early use from those of routinised, cross-firm use (Zhu, Kraemer and Xu, 2006), but this insight has not been built into a Digital Twin maturity model. None of the existing models separates the use-case level decision to adopt from the enterprise level or ecosystem level achievement of scaling, or makes explicit the determinants that couple the two.

3.4 Research Gaps

Three gaps follow, each grounded in a trend observed across the focused corpus. First, the Digital Twin delivers clear benefits, but its uptake in capital-intensive industries remains confined to isolated pilots, and the causes are not well explained (Hamidishad et al., 2025; Richter, Campbell and Riedl, 2025). Second, maturity models describe growth as a single linear staircase and do not separate adoption from scaling, even though assimilation research shows the two are driven by different factors (Zhu, Kraemer and Xu, 2006; Liang et al., 2007). Third, the organisational (TOE) and individual (UTAUT) lenses are typically used separately and for adoption only; few studies combine them, and fewer still apply them to both the adoption and the scaling of a Digital Twin (Atencio and Alzamora, 2025). Closing these gaps requires a framework that defines adoption maturity and scaling maturity as distinct but coupled constructs and integrates the organisational, individual, and assimilation lenses.

4. Proposed Conceptual Maturity Framework

The proposed Digital Twin Adoption-and-Scaling Maturity (DT-ASM) Framework addresses the limitations of linear models by separating the maturity question into two interrelated but distinct journeys: an adoption maturity journey at the use-case level, and a scaling maturity journey at the firm or ecosystem level. The two journeys are coupled through four cross-cutting determinants that have emerged from the synthesis: risk exposure, resource allocation cycles, ecosystem maturity, and organisational alignment (Schuh et al., 2017; Plekhanov, Franke and Netland, 2023; Atencio and Alzamora, 2025; Hamidishad et al., 2025).

4.1 Architecture of the Maturity Framework

The framework is structured around two five-stage maturity ladders. The Adoption Maturity ladder (Table 1) describes how an organisation moves from awareness to routinised use within a defined scope; the Scaling Maturity ladder (Table 2) describes how the firm, with its ecosystem, moves from a single routinised twin to federated, ecosystem-level capability.

Table 1: Adoption maturity ladder

Maturity Stage	Description
A1. Awareness and strategic framing	Recognises the twin as a strategic option and links a vision to corporate strategy; corresponds to the initiation stage of assimilation, in which the firm evaluates potential benefits and scans for fitting innovations (Zhu, Kraemer and Xu, 2006; Schuh et al., 2017).
A2. Pilot selection and sociotechnical readiness	Selects a bounded use-case where data, instrumentation, and sponsorship align - the assimilation adoption decision - where success turns on sociotechnical alignment rather than technical skill alone (Atencio and Alzamora, 2025).
A3. Pilot deployment and validation	Implements a model or shadow on near-real-time data, validated against ground truth; as end-users engage, UTAUT acceptance drivers begin to dominate (Venkatesh et al., 2003; Dwivedi et al., 2019).
A4. Operational deployment	Evolves into a full twin with bidirectional feedback embedded in operational control; top-management support and absorptive capacity become decisive (Liang et al., 2007; Shao, Feng and Hu, 2012).
A5. Routinised use within scope	Monitored, maintained, retrained, and audited as business-as-usual, the routinisation stage, where an assimilation gap often leaves widespread use lagging initial adoption (Zhu, Kraemer and Xu, 2006; Hasgall, Ahituv and Naveh, 2019).

Table 2: Scaling maturity ladder

Maturity Stage	Description
S1. Single use-case	Builds the twin as a replicable pattern, for example data contracts, model artefacts, validation protocols, governance roles, economic baselines, so the next deployment is cheaper and faster (Schuh et al., 2017; Hamidishad et al., 2025).
S2. Multi-asset replication	Replicates the pattern across similar assets; CAPEX and OPEX logics merge into a TOTEX view with staged, real-option financing (Hamidishad et al., 2025).
S3. Cross-domain federation	Federates twins into a system of systems; because twin interpretations are heterogeneous, federation needs semantic alignment and shared standards, not data exchange alone (Cimino, Ferretti and Leva, 2021; Liu et al., 2024).

Maturity Stage	Description
S4. Ecosystem twin and platform orchestration	Connects the federated twin with suppliers, customers, and regulators; value shifts from inside firm boundaries to across the ecosystem, bringing platform economics and multi-tenant governance to the fore (Su et al., 2022; Plekhanov, Franke and Netland, 2023).
S5. Self-evolving industrial ecosystem	Processes self-organise through agentic, AI-augmented decision logic under industry-wide standards; advantage is no longer the individual twin but the firm's position in the ecosystem it orchestrates (Grieves, 2025).

The two ladders can be read together as a single diagnostic space. Plotting adoption maturity against scaling maturity produces the DT-ASM matrix (Figure), in which any organisation occupies a cell defined by its position on each ladder. The matrix turns the framework into a map: it shows not only where a firm stands but also the direction and balance of its progress, and it distinguishes three qualitatively different trajectories.

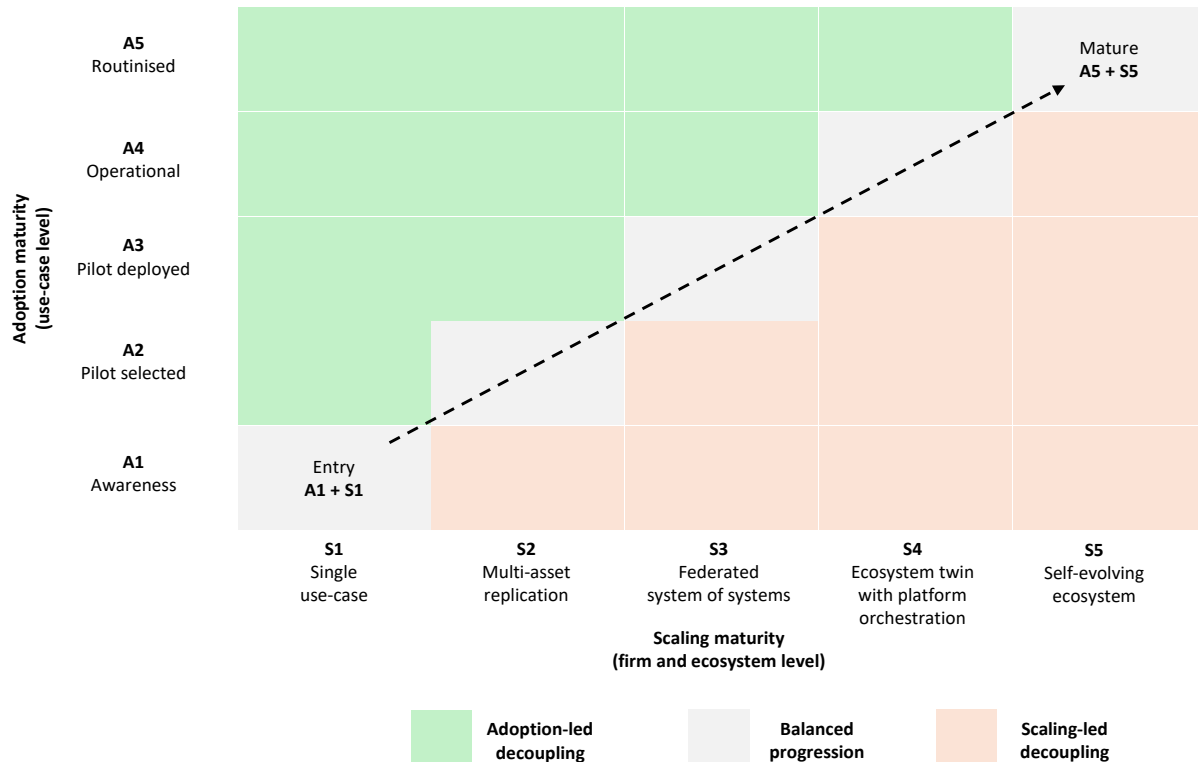


Figure 1: The Digital Twin Adoption-and-Scaling Maturity (DT-ASM) Matrix

Cells on the diagonal represent balanced progression, where use-case level capability and ecosystem-level scaling advance in step. Cells above the diagonal represent adoption-led decoupling, where an organisation builds sophisticated twins internally but has yet to replicate or federate. Cells below the diagonal represent scaling-led decoupling, where ecosystem platforms enable rapid scaling without deep use-case level adoption. Movement is expected to be non-linear where an organisation may advance on one axis, stall, or regress. Therefore, adoption and scaling maturity are interrelated but strategically separable.

4.2 Cross-cutting Determinants

Four cross-cutting determinants moderate progress on each ladder and govern the coupling between them:

- *Risk exposure*: the changing portfolio of technical, financial, organisational, regulatory, and systemic risks faced at each stage. Adoption stages emphasise use-case and vendor risk; scaling stages emphasise integration, model-drift, cybersecurity, partner, and systemic risks (Roberts et al., 2021; Hamidishad et al., 2025).
- *Resource allocation cycles*: the governance logic and time horizon of investment. Adoption is dominated by project CAPEX and short cycles; scaling is dominated by total expenditure, real options, and long cycles, with explicit budget for model maintenance, retraining, and ecosystem participation (Schuh et al., 2017; Hamidishad et al., 2025).

- *Ecosystem maturity*: the readiness of standards, platforms, supplier networks, talent markets, regulatory frameworks, and industrial commons that surround the firm. A firm cannot scale faster than its ecosystem allows (Cimino, Ferretti and Leva, 2021; Plekhanov, Franke and Netland, 2023; Watts et al., 2025).
- *Organisational alignment*: the alignment of strategy, structure, leadership style, culture, and end-user behaviour. Adoption requires vertical alignment; scaling requires networked alignment, including with external partners and standards bodies (Shao, Feng and Hu, 2012; Haryanti, Rakhmawati and Subriadi, 2023).

Each determinant pulls differently at the two stages, as summarised in Table 3. This role differentiation is what allows a firm to be constrained by one determinant during adoption and by another during scaling.

Table 3: Differentiated role of each determinant across the adoption and scaling ladders

Determinant	Role in Adoption	Role in Scaling
Risk exposure	Use-case and vendor risk dominate; low tolerance keeps pilots small.	Integration, model-drift, cybersecurity, and systemic risk dominate.
Resource allocation cycles	Short project CAPEX cycles fund pilots.	Long TOTEX and real-option logic fund replication and federation.
Ecosystem maturity	Limited effect; firms can pilot in isolation.	Strong effect; standards and platforms set the speed limit for scaling.
Organisational alignment	Vertical alignment and leadership support are decisive.	Networked alignment with external partners becomes decisive.

The ladders are coupled in three ways: adoption successes create the patterns and credibility scaling requires; scaling expectations shape adoption-stage choices about vendors and architectures; and the four determinants act on both. They are also strategically decoupled as the matrix shows.

4.3 Propositions and Operationalisation

The framework yields seven propositions that constitute a directly testable agenda; each is formalised as a hypothesis in ongoing empirical work:

- P1.** Adoption maturity and scaling maturity are two empirically distinct constructs, not a single dimension.
- P2.** The five adoption stages (A1–A5) form a cumulative, correctly ordered progression.
- P3.** The five scaling stages (S1–S5) form a cumulative, correctly ordered progression.
- P4.** An organisation can reach high adoption maturity while remaining low on scaling maturity, and vice versa (decoupling).
- P5.** Each of the four determinants significantly predicts progression along the adoption ladder.
- P6.** Each of the four determinants significantly predicts progression along the scaling ladder.
- P7.** The relative weight of the four determinants differs between the adoption and the scaling ladder.

The framework is designed to be operationalised through maturity ladder validation (P1, P2, P3), where each ladder is measured both by a single ordered self-classification and by a cumulative battery of stage capability items using ordinal structure testing. The determinant paths (P5, P6, P7) are estimated as two structural models with adoption and scaling as endogenous constructs; and decoupling (P4) is examined by locating firms on the adoption-by-scaling matrix. The intended validation context is capital-intensive, safety-critical, and data-rich industrial settings.

5. Theoretical Implications

The DT-ASM framework contributes to theoretical development by disaggregating Digital Twin maturity into two distinct constructs: Adoption Maturity and Scaling Maturity. This paper introduced four explicit cross-cutting determinants taken from classical technology adoption theories (Davis, 1989; Tornatzky and Fleischer, 1990; Venkatesh et al., 2003; Dwivedi et al., 2019), technology assimilation research (Zhu, Kraemer and Xu, 2006; Hasgall, Ahituv and Naveh, 2019), leadership and psychological frameworks (Shao, Feng and Hu, 2012; Roberts

et al., 2021), and digital transformation literatures (Schuh et al., 2017; Plekhanov, Franke and Netland, 2023). From a parsimony perspective, two coupled ladders and four determinants are harder to operationalise than a single staircase, therefore the propositions and measurement strategy are designed to justify this added complexity.

6. Practical Implications

For industry leaders, the framework reframes the central strategic question. Rather than asking how mature is our Digital Twin, leaders are invited to ask: how mature is our adoption capability for the use-cases we are pursuing; how mature is our scaling capability for the asset portfolio, value chain, and ecosystem we operate in; and where is the binding constraint, in our risk posture, in our resource cycles, in our ecosystem, or in our organisational alignment.

The DT-ASM framework prescribes balanced, capability-aware progress along both ladders, with deliberate attention to which determinant is currently binding. Doubling down on technology investment without addressing organisational alignment leaves adoption maturity stalled at level A3 or A4 (Shao, Feng and Hu, 2012; Roberts et al., 2021). Pursuing aggressive scaling targets without first achieving routinised use at level A5 produces fragile deployments that collapse under operational stress (Hamidishad et al., 2025). Assuming that ecosystem standards will arrive on demand leaves firms exposed when they do not (Cimino, Ferretti and Leva, 2021; Watts et al., 2025).

7. Limitations and Future Research

The framework is conceptual and synthetic, and it inherits the limitations of the literatures from which it draws. The five-stage articulation of each ladder is a heuristic rather than an empirical partition. Real organisations are unlikely to occupy a single stage cleanly, and both ladders are likely to exhibit local cycles of regression and recovery, especially when leadership turnover, technology shocks, or regulatory changes occur. Further research follows directly. Empirical validation of the dual ladders is a priority: cross-sectoral mixed-methods studies are needed to test the seven propositions set out in Section 4.3.

8. Conclusion

The synthesis presented in this paper addresses the limitation of single-axis maturity models by separating adoption maturity from scaling maturity, articulating each as a five-stage ladder, and identifying four cross-cutting determinants that govern progress along and between the ladders: risk exposure, resource allocation cycles, ecosystem maturity, and organisational alignment. None of the existing maturity models, from the acatech Index (Schuh et al., 2017) and the Extended Digital Maturity Model (Haryanti, Rakhmawati and Subriadi, 2023) to CITYSTEPS (Haraguchi, Funahashi and Biljecki, 2024) and the capability-based model (Liu et al., 2024), separates the decision to adopt from the capability to scale. The DT-ASM framework makes that separation, and the determinants that couple the two ladders, explicit and testable.

Empirical applicability rests on three conditions: measurement instruments that operationalise each stage through observable criteria; access to organisations at different positions on the DT-ASM matrix representing coupled and decoupled progression; and longitudinal or retrospective data to evaluate movement between stages rather than static positions. Within these conditions, the framework supports three classes of action: a foundation for empirical validation by researchers, a diagnostic instrument for industry leaders to identify binding constraints, and a clearer view for policymakers of the ecosystem investments covering standards, platforms, talent, and regulation needed for scalable Digital Twin deployment.

Ethics Declaration

This study involved no human or animal subjects and adhered to ethical research standards. All sources used are publicly available or properly cited.

AI Declaration

AI tools were used only for language editing. All ideas, analysis, and interpretations are the authors' own.

References

- Atencio, G.S. and Alzamora, R.B. (2025) 'Extending the TOE framework for digital twin adoption in Latin American project management', *Ingeniería e Investigación*, 45(3), e120958. doi: 10.15446/ing.investig.120958.
- Augusto, J.C., Callaghan, V., Cook, D., Kameas, A. and Satoh, I. (2013) 'Intelligent Environments: a manifesto', *Human-centric Computing and Information Sciences*, 3(12), pp. 1–18. doi: 10.1186/2192-1962-3-12.
- Cimino, C., Ferretti, G. and Leva, A. (2021) 'Harmonising and integrating the Digital Twins multiverse: a paradigm and a toolset proposal', *Computers in Industry*, 132, 103501. doi: 10.1016/j.compind.2021.103501.
- Davis, F.D. (1989) 'Perceived usefulness, perceived ease of use, and user acceptance of information technology', *MIS Quarterly*, 13(3), pp. 319–340. doi: 10.2307/249008.
- Dwivedi, Y.K., Rana, N.P., Jeyaraj, A., Clement, M. and Williams, M.D. (2019) 'Re-examining the Unified Theory of Acceptance and Use of Technology (UTAUT): Towards a Revised Theoretical Model', *Information Systems Frontiers*, 21(3), pp. 719–734. doi: 10.1007/s10796-017-9774-y.
- Grieves, M. (2025) 'Digital Twin: Phases and Futures', *Digital Engineering*, 6, 100053. doi: 10.1016/j.dte.2025.100053.
- Grieves, M. and Vickers, J. (2017) 'Digital Twin: mitigating unpredictable, undesirable emergent behavior in complex systems', in Kahlen, F.-J., Flumerfelt, S. and Alves, A. (eds.) *Transdisciplinary Perspectives on Complex Systems*. Cham: Springer, pp. 85–113. doi: 10.1007/978-3-319-38756-7_4.
- Hamidishad, N., Barbosa, R.S., Allahyarzadeh-Bidgoli, A. and Yanagihara, J.I. (2025) 'Digital twin frameworks for oil and gas processing plants: a comprehensive literature review', *Processes*, 13(11), 3488. doi: 10.3390/pr13113488.
- Haraguchi, M., Funahashi, T. and Biljecki, F. (2024) 'Assessing governance implications of city digital twin technology: a maturity model approach', *Technological Forecasting and Social Change*, 204, 123409. doi: 10.1016/j.techfore.2024.123409.
- Haryanti, T., Rakhmawati, N.A. and Subriadi, A.P. (2023) 'The extended digital maturity model', *Big Data and Cognitive Computing*, 7(1), 17. doi: 10.3390/bdcc7010017.
- Hasgall, A.E., Ahituv, N. and Naveh, N. (2019) 'Effective assimilation of technological innovation in an organization characterized as a Complex Adaptive System (CAS)', *Journal of Innovation Management*, 7(2), pp. 38–58. doi: 10.24840/2183-0606_007.002_0004.
- Hutajulu, S., Dhewanto, W. and Prasetyo, E.A. (2021) 'An agent-based model for 5G technology diffusion in urban societies: simulating two development scenarios', *Sustainability*, 13(22), 12698. doi: 10.3390/su132212698.
- Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020) 'Characterising the Digital Twin: a systematic literature review', *CIRP Journal of Manufacturing Science and Technology*, 29, pp. 36–52. doi: 10.1016/j.cirpj.2020.02.002.
- Liang, H., Saraf, N., Hu, Q. and Xue, Y. (2007) 'Assimilation of enterprise systems: the effect of institutional pressures and the mediating role of top management', *MIS Quarterly*, 31(1), pp. 59–87. doi: 10.2307/25148781.
- Liu, Y., Feng, J., Lu, J. and Zhou, S. (2024) 'A review of digital twin capabilities, technologies, and applications based on the maturity model', *Advanced Engineering Informatics*, 62, 102592. doi: 10.1016/j.aei.2024.102592.
- Plekhanov, D., Franke, H. and Netland, T.H. (2023) 'Digital transformation: a review and research agenda', *European Management Journal*, 41(6), pp. 821–844. doi: 10.1016/j.emj.2022.09.007.
- Richter, F., Campbell, K. and Riedl, J. (2025) 'Lost in translation: why digital twins thrive in research but falter in politics and public administration', *Data & Policy*, 7, e71. doi: 10.1017/dap.2025.10027.
- Roberts, R., Flin, R., Millar, D. and Corradi, L. (2021) 'Psychological factors influencing technology adoption: a case study from the oil and gas industry', *Technovation*, 102, 102219. doi: 10.1016/j.technovation.2020.102219.
- Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M. and Wahlster, W. (eds.) (2017) *Industrie 4.0 Maturity Index: managing the digital transformation of companies (acatech STUDY)*. Munich: Herbert Utz Verlag.
- Senna, P.P., Barros, A.C., Bonnin Roca, J. and Azevedo, A. (2023) 'Development of a digital maturity model for Industry 4.0 based on the technology-organization-environment framework', *Computers & Industrial Engineering*, 185, 109645. doi: 10.1016/j.cie.2023.109645.
- Shao, Z., Feng, Y. and Hu, Q. (2012) 'How leadership styles impact enterprise systems success throughout the lifecycle: a theoretical exploration', *Proceedings of the 45th Hawaii International Conference on System Sciences*. Maui, HI, 4–7 January. IEEE, pp. 4692–4701. doi: 10.1109/HICSS.2012.303.
- Sharma, A., Kosasih, E., Zhang, J., Brintrup, A. and Calinescu, A. (2022) 'Digital Twins: state of the art theory and practice, challenges, and open research questions', *Journal of Industrial Information Integration*, 30, 100383. doi: 10.1016/j.jii.2022.100383.
- Su, C., Han, Y.R., Tang, X., Jiang, Q., Wang, T. and He, Q. (2022) 'Research on the strategy evolution of knowledge innovation in an enterprise digital innovation ecosystem: kinetic and potential perspectives', *IEEE Access*, 10, pp. 78764–78779. doi: 10.1109/ACCESS.2022.3194071.
- Tornatzky, L.G. and Fleischer, M. (1990) *The processes of technological innovation*. Lexington: Lexington Books.
- Venkatesh, V., Morris, M.G., Davis, G.B. and Davis, F.D. (2003) 'User acceptance of information technology: toward a unified view', *MIS Quarterly*, 27(3), pp. 425–478. doi: 10.2307/30036540.
- Watts, G., Munir, M., Underwood, J., Hales, D., Sadabad, M.M., Balogun, T., Coates, P. and Lim, L. (2025) 'Lack of digital twin policy as a barrier to sustainability, carbon targets, and SDG achievement', *Carbon Footprints*, 4, 27. doi: 10.20517/cf.2025.20.
- Zhu, K., Kraemer, K.L. and Xu, S. (2006) 'The process of innovation assimilation by firms in different countries: a technology diffusion perspective on e-business', *Management Science*, 52(10), pp. 1557–1576. doi: 10.1287/mnsc.1050.0487.