LAMPD: a combined lean and agile model for product development

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Abstract: Despite apparent differences, Lean and Agile product development methodologies share significant commonalities. This research integrates Lean and Agile product development methodologies for hardware contexts through a unified lean and agile model for product development (LAMPD). We examined case study implementations of both approaches, explored their integration potential, developed a comprehensive model, and evaluated its potential outcomes through expert assessment. Working with Atlas Copco Henrob, we systematically harmonised Lean PD principles with Agile frameworks by mapping relationships between 12 Agile Principles and the 5-phase Set-Based Concurrent Engineering process, identifying synergies and resolving conflicts. The resulting model integrates stage-gate processes with Scrum ceremonies and Kanban visualisation techniques across three development phases. Expert evaluation with 17 R&D professionals revealed strong support for the model, with practitioners identifying nine benefit categories, including enhanced communication, better risk management, and improved knowledge capture. The LAMPD process model provides a structured method to enhance efficiency and adaptability in hardware development while challenging traditional methodology dichotomies.

Keywords: lean product development; agile product development; set-based concurrent engineering; SBCE; hardware development; Scrum; Kanban; stage-gate process; methodology integration; concurrent engineering.

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1 Introduction

Companies must continuously adapt their product development (PD) approaches to maintain competitiveness (Civelek et al., 2023; Blais et al., 2023; Batista et al., 2023). This paper examines lean product development (Lean PD) and Agile Product Development (Agile PD) as complementary approaches. Lean PD emphasises value creation through waste elimination and knowledge-based development, while Agile PD focuses on iterative development and adaptability. Set-Based Concurrent Engineering (SBCE) represents the Lean PD approach, with Agile examined through its 12 Principles and the Scrum and Kanban frameworks.

Despite their success, integrating these methodologies for hardware PD presents challenges. Current research demonstrates both approaches' efficacy in isolation: Lean PD has yielded positive outcomes in hardware development (Battistella et al., 2023), whilst Agile has proven effective in software (Palsodkar et al., 2023). Recent studies reveal promising benefits from applying Agile principles to mechanical and hardware projects (Ciric et al., 2018; de Vasconcelos Gomes et al., 2021; Riascos et al., 2024). Ni et al. (2020) developed a Lean and Agile multi-dimensional Process for healthcare technology, though it lacks explicit integration of SBCE, Scrum, or Kanban approaches for hardware development.

However, significant gaps exist in understanding how these methodologies can be effectively combined. Limited research has addressed their integration (Wangsa et al., 2022), and in particular, within hardware development contexts. The absence of a unified model that leverages both approaches' strengths while addressing potential conflicts hinders organisations from realising their full benefits. This gap is particularly significant given modern PD's increasing complexity, which often involves hardware and software components requiring different development approaches.

This study addresses a critical research gap: the absence of a comprehensive model integrating Lean PD and Agile methodologies for hardware development. Our integration approach employs systematic principle mapping and harmonisation analysis to create a unified process model that maintains both approaches' characteristics while addressing hardware-specific constraints. The methodology builds upon previous SBCE implementations (Al-Ashaab et al., 2013), extending them through integration with Agile principles. The practical significance lies in providing organisations with a structured model to enhance efficiency and adaptability in hardware development, potentially reducing development time and costs while improving product quality. Theoretically, this research advances our understanding of methodology integration, challenging the traditional separation between Lean and Agile paradigms and extending set-based engineering theory into more flexible development contexts.

2 Research methodology

2.1 Research philosophy and approach

This research adopts a mixed-methods approach combining systematic literature review, expert consultation, and model development following engineering design research protocols (Blessing and Chakrabarti, 2009; Wynn and Clarkson, 2018). Our approach aligns with the Design Research Methodology framework (Eckert et al., 2019), integrating expert judgement with systematic model development to ensure theoretical grounding and practical applicability.

2.2 Literature review and data collection

Our methodology combines literature review, case study analysis, and practitioner validation. We evaluated the current understanding of both methodologies through database analysis (IEEE Xplore, ScienceDirect, ProQuest, Scopus, Google Scholar), using keywords including 'Agile PD', 'Agile in hardware', and 'implementation of Agile', with a similar approach for Lean PD. Our focus was identifying synergies and resolving conflicts between Lean PD and Agile Principles to develop a unified process model. SBCE is introduced as a key Lean PD enabler, with Khan's (2012) 5-phase, 21-step process model forming the LAMPD foundation. From 146 papers matching the search criteria, we refined to 57 based on empirical evidence, clear outcomes description, and hardware development relevance. Case studies from various industries were reviewed to evaluate the benefits of both approaches, with data categorised into benefit types, organisational contexts, and critical success factors.

2.3 Research design

This study investigates how complementary attributes of Lean and Agile PD approaches can be harmonised to enhance hardware PD. This harmonisation of guiding philosophies, practices, and reported outcomes involved two phases.

2.3.1 Phase 1: questionnaire and semi-structured interviews

Five senior Agile practitioners from UK technology companies provided expert judgement to harmonise Agile Principles with Khan's (2012) SBCE Process Model through questionnaires and semi-structured interviews. Their input on Agile principles' effectiveness in hardware PD was synthesised using thematic analysis (Fona, 2024) to identify patterns and agreements.

2.3.2 Phase 2: integration and model development

In the second phase, a systematic mapping exercise identified synergies and conflicts between the SBCE Process Model, Scrum, Kanban, and the company's current PD process. This mapping used integration matrices to score alignment between methodological elements, identifying areas of natural synergy and potential conflict. Resolutions were developed for identified conflicts using multiple criteria, including root cause analysis, implementation feasibility, trade-off evaluations, and compatibility with organisational culture. Synergies were then leveraged to create the novel model across three PD phases:

1. project definition
2. project feasibility
3. project realisation.

The theoretical foundations established in the literature and the integration points identified in Section 5 were continually referenced throughout the model's iterative development. This approach builds upon methodology transformation processes established in previous SBCE implementation research (Al-Ashaab et al., 2021), extending them to incorporate Agile frameworks.

2.4 Expert evaluation

The resulting model was evaluated via a survey of seventeen R&D department members, providing an expert assessment of the model's potential benefits and applicability. All participants were professional engineers familiar with Agile and Lean principles and trained on the new model's purpose and application. Respondents included three engineering managers, four senior engineers, and 10 engineers, with 10 respondents having over 10 years of engineering experience. The survey methodology assessed practitioners' perceptions of the model's potential benefits before full implementation, providing insights into expected outcomes while identifying areas of uncertainty requiring attention during rollout. This approach aligns with the DRM framework's expert evaluation phase, allowing model refinement based on practitioner feedback before implementation testing.

3 Literature review

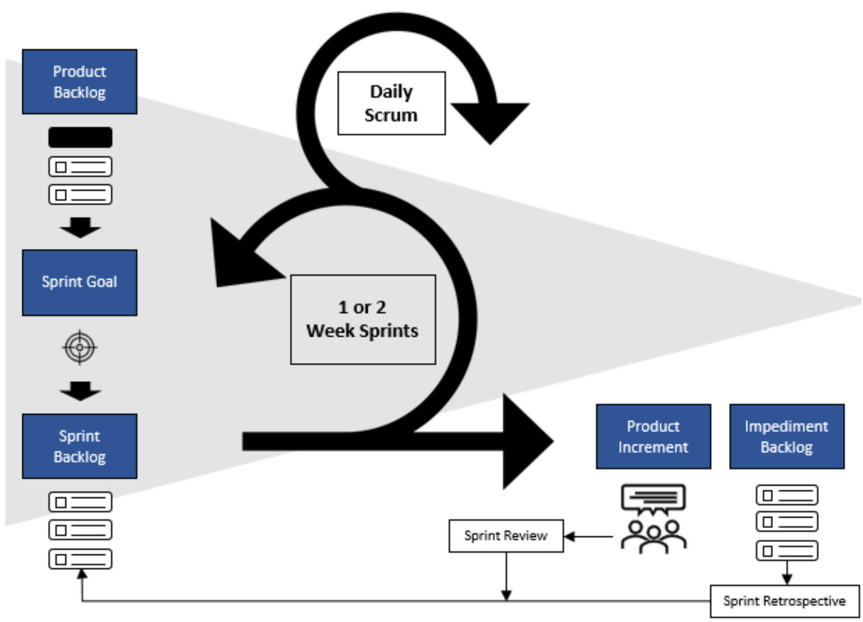
3.1 Lean and agile approaches for product development

The following sections examine Lean and Agile methodologies, establishing the foundation for understanding how these approaches can be combined in the LAMPD process model. We identify key integration opportunities by systematically exploring their respective principles, frameworks, benefits, and applications in hardware contexts while acknowledging each methodology's unique challenges.

3.2 Agile principles and frameworks for hardware development

Agile methodologies emerged in response to 'waterfall' development approaches' rigidity (Royce, 1970), culminating in the Agile Manifesto with its four values and 12 principles (Böhmer et al., 2017). Gren and Lenberg (2020) define agility as responsiveness when complete knowledge is unavailable. Scrum, the most prominent Agile framework (Figure 1), comprises three cycles, progressively improving customer value through iteration.

Figure 1 The scrum framework (see online version for colours)

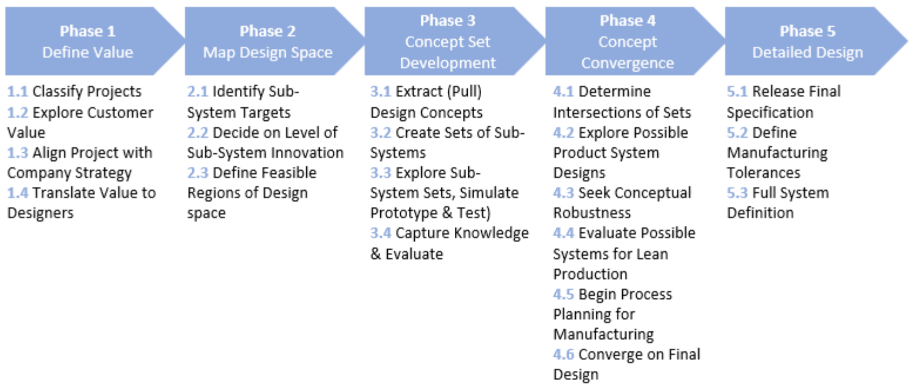


Source: Adapted from Lawong and Akanfe (2025)

3.3 Lean product development and set-based concurrent engineering

Morgan and Liker (2006) identified 13 core Lean PD principles across Process, People, and Technology categories. Khan et al. (2011) define Lean PD as 'value-focused PD' based on five enablers: SBCE process, chief engineer leadership, value-focused planning, knowledge-based environment, and continuous improvement. SBCE develops multiple design solutions simultaneously and reduces these through trade-off analysis until identifying the optimal solution (Sobek et al., 1999; Rismiller et al., 2023). Khan's (2012) 5-phase, 21-step SBCE Process Model (Figure 2) guides teams from initial value definition through progressively narrowing alternatives to the final specification.

Figure 2 The LeanPD SBCE process model (see online version for colours)



Source: Khan (2012)

3.4 Benefits of individual approaches and integration opportunities

While SBCE poses challenges like extended development times and higher initial costs, it has demonstrated the capacity to spur innovation, facilitate knowledge reuse, and deliver superior outcomes in contexts of complexity, uncertainty, and risk. Implementation of Lean PD and Agile as distinct approaches has demonstrated different advantages. The benefits realised through implementing Agile in separate software and hardware PD contexts differ due to variations in the development lifecycle approach, feedback loop speed, and practical constraints like specialised equipment requirements for hardware development. The independent and related benefits realised by case study implementations include:

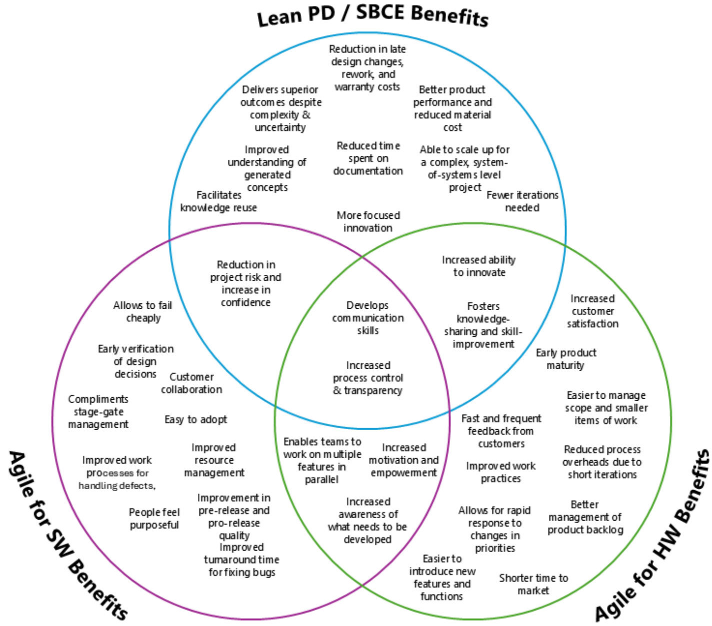
1 *Agile for Software Development* (Palopak and Huang, 2024; Sarkar et al., 2024): Improved team communication, increased customer satisfaction, faster delivery cycles, higher quality products, reduced documentation overhead, and enhanced adaptability to changing requirements.

2 *Agile for Hardware Development* (Weichbroth, 2022; Scharold and Paetzold-Byhain, 2024): Improved collaboration, better risk management, and more efficient handling of complex interdependencies.

3 *Lean PD/SBCE* (Raudberget et al., 2010; Khan, 2012; Al-Ashaab et al., 2021; Spinelli et al., 2022): Reduced late design changes, better knowledge management, and enhanced innovation capability.

The overlapping benefits (Figure 3) suggest significant potential for synergistic integration, particularly in communication, quality, and complexity management.

Figure 3 Venn diagram showing the benefits realised by case study implementations of LeanPD and agile (see online version for colours)



4 Research gap and objectives

While Agile methodologies have proven successful in software development, their application to hardware PD remains under-explored. The empirical foundation supporting hardware-focused implementations of Agile principles, Scrum, and Kanban remains inadequate, particularly in understanding how these approaches can be integrated to address hardware development's unique physical constraints and longer iteration cycles.

When examining SBCE's applications and practices, while active research surrounds it, its industrial implementation requires attention. There is a noticeable gap between research direction and broader practical adoption, and there is limited evidence concerning SBCE's integration with complementary PD approaches like Agile (Toche et al., 2020; Shallcross et al., 2020). Furthermore, there is limited evidence of how combined Agile-Lean PD approaches can be successfully integrated with established stage-gate PD processes prevalent in hardware industries. Without proven integration frameworks or models, researchers and practitioners often resort to ad-hoc combinations of methodologies, creating a significant gap between theory and practical application. This research aims to address these gaps through four key objectives:

1 Examine case study implementations of Lean PD and Agile PD and their respective benefits.

2 Explore the feasibility of combining Lean PD and Agile principles and frameworks through systematic mapping and harmonisation analysis, establishing a theoretical foundation for process integration.

3 Develop a unified Lean and Agile Model for PD (LAMPD).

4 Assess whether this integrated model could yield superior PD outcomes compared to individual implementations.

By addressing these objectives, this research contributes to academic understanding and practical application of integrated PD methodologies, particularly for hardware-focused organisations.

5 Combining Lean PD and agile: the lean-agile model for product development (LAMPD)

5.1 Harmonisation approach

Lean PD and Agile approaches were harmonised systematically in four steps to identify alignments and gaps.

Step 1: The 12 Agile Principles were mapped against Morgan and Liker's 13 core Lean PD principles (2006), with direct relationships marked at Figure 4. In Figure 4, a (◆) indicates a direct relationship between the respective principles; grey shading indicates no connection could be identified. This mapping revealed key differences arising from their distinct origins:

1 *Agile Principle 7 (Working Software is the Primary Measure of Progress)*: This is not directly addressed by Lean PD principles as Lean PD encompasses broader engineering disciplines.

2 Three Lean PD principles not explicitly addressed by Agile Principles:

  a *Step 8 (Fully integrate suppliers into the PD system)*: This is likely because Agile was initially designed for software projects rather than complex systems involving multiple suppliers.

  b *Step 11 (Adapt technology to fit your people and process)*: While Agile is adaptable, it doesn't explicitly focus on technology adaptation.

  c *Step 13 (Use powerful tools for standardisation and organisational learning)*: Agile focuses more on principles and values rather than prescribing specific tools.

Step 2: The 12 Agile Principles were mapped against the 5 phases and 21 steps of Khan's SBCE Process Model (2012) (Figure 5). This analysis revealed substantial overlap, indicating mutual support between Agile Principles and Lean PD objectives. The mapping identified where Agile Principles aligned with specific SBCE process phases (☐) and which could be applied across multiple activities (◆). While these approaches initially seem contradictory, they appear highly complementary when SBCE is positioned as a structured process within an Agile framework.

Figure 4 Harmonising agile's 12 principles and LeanPD's 13 core principles

Agile Principle \ LeanPD Principle	1. Process: Step 1: Establish Customer-Defined Value	1. Process: Step 2: Front-load the PD Process	1. Process: Step 3: Level PD Process Flow	1. Process: Step 4: Rigorous Alignment	2: Skilled People: Step 5: Chief Engineer System	2: Skilled People: Step 6: Balance Func' Expertise & Cross-Func' Integration	2: Skilled People: Step 7: Engineering Competence	2: Skilled People: Step 8: Integrate Suppliers across PD	2: Skilled People: Step 9: Learning & Continuous Improvement	2: Skilled People: Step 10: Excellence & Improvement Culture	3: Tools & Technology: Step 11: Adaptive Technologies	3: Tools & Technology: Step 12: Align Through Visual Communication	3: Tools & Technology: Step 13: Tools for Standardisation & Org' Learning
Principle 1: Customer Satisfaction	◆												
Principle 2: Welcome Changing Requirements		◆											
Principle 3: Deliver Working Software Frequently		◆											
Principle 4: Business People & Developers Work Together						◆							
Principle 5: Build Projects around Motivated Individuals					◆								
Principle 6: Promote Face-to-Face Conversation												◆	
Principle 7: Working Software Measures Progress													
Principle 8: Sustainable Development			◆										
Principle 9: Technical Excellence							◆						
Principle 10: Simplicity is Essential				◆									
Principle 11: Self-Organising Teams					◆								
Principle 12: Team Reflection									◆	◆			

Step 3: Conceptual harmonisation of the SBCE Process Model with the Scrum framework revealed potential synergies for integrating Scrum's time-bound cycles with SBCE phases to enhance time management, outcome integrity, cross-function collaboration, feedback, and delivery of high-value outcomes.

Figure 5 Mapping 12 agile principles against SBCE phases and steps

Agile Principle \ SBCE Phases & Steps	Phase 1: Value Research				Phase 2: Map Design Space			3: Concept Set Development					4: Concept Convergence						5: Detailed Design		
	Step 1.1 Classify Project Type	**Step 1.2** Explore Customer Value	**Step 1.3** Align with Company Strategy	**Step 1.4** Translate Value to Designers	**Step 2.1** Identify Sub-System Targets	**Step 2.2** Decide Level of Sub-System Innovation	**Step 2.3** Define Feasible Regions of Des' Space	**Step 3.1** Pull Design Concepts	**Step 3.2** Create Sets for each Sub-System	**Step 3.3** Explore Sub-System Sets: Proto & Test	**Step 3.4** Capture Knowledge & Evaluate	**Step 3.5** Communicate Set to Others	**Step 4.1** Determine Set Intersections	**Step 4.2** Explore System Sets	**Step 4.3** Seek Conceptual Robustness	**Step 4.4** Evaluate Sets for Lean Production	**Step 4.5** Begin Process Planning for Manuf'g	**Step 4.6** Converge on Final Set of Sub-System Concepts	**Step 5.1** Release of First Specification	**Step 5.2** Manuf'g Provides Tolerances	**Step 5.3** Full System Definition
Principle 1: Customer Satisfaction		□			□																
Principle 2: Welcome Changing Requirements	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			
Principle 3: Deliver Working Software Frequently									□	□											
Principle 4: Business People & Developers Work Together	□	□	□	□																	
Principle 5: Build Projects around Motivated Individuals								□	□	□	□	□									
Principle 6: Promote Face-to-Face Conversation	□	□	□	□								□									□
Principle 7: Working Software Measures Progress							□					□						□			□
Principle 8: Sustainable Development					◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			
Principle 9: Technical Excellence					◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			
Principle 10: Simplicity is Essential					◆	◆	◆	◆	◆	◆	◆		◆	◆	◆	◆	◆	◆			
Principle 11: Self-Organising Teams								◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			
Principle 12: Team Reflection					◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆			

Step 4: Kanban principles were conceptually integrated with the SBCE Process Model to identify potential synergy opportunities in four key areas:

1 *Task tracking*: Adapt Kanban boards to track multiple design sets simultaneously using swim lanes for each design alternative, with visual signals representing set progression and knowledge capture.

2 *Knowledge Management*: Use pull-based flow to manage knowledge generation, with downstream processes signalling their information needs from upstream activities.

3 *Capacity Management*: Apply work-in-progress limits to balance resources across multiple design alternatives, preventing overload while ensuring adequate exploration.

4 *Coordination*: Use cycle time metrics to coordinate convergence timing for different design sets, preventing premature options narrowing while managing dependencies.

5.2 Harmonisation challenges

Harmonising SBCE with Agile Principles presents several key challenges:

1 *Alignment*: Misalignment between SBCE phases and Scrum sprints requires careful synchronisation.

2 *Balancing feedback*: Agile's iterative feedback may conflict with SBCE's structured approach.

3 *Managing complexity*: SBCE involves numerous dependencies, where Kanban boards can help visualise workflows.

4 *Prioritisation*: SBCE's upfront innovation focus may conflict with Agile's dynamic reprioritisation.

5 *Performance measurement*: Different success metrics require integrated measurement systems.

6 *Cultural alignment*: Change management is necessary for teams accustomed to single approaches.

Our analysis revealed substantial complementarity when positioning SBCE within a broader Agile framework. This integration addresses fundamental hardware PD tensions: whilst Agile provides flexibility for evolving requirements but lacks guidance on managing multiple design alternatives, SBCE offers tools for managing design sets but traditionally lacks rapid adaptation mechanisms. These identified challenges formed a critical reference point for the model development process described in Section 6. Each challenge was systematically addressed through specific integration mechanisms and adaptation of methodological elements to ensure the resulting LAMPD model maintained the strengths of both approaches while minimising tensions between them. The harmonisation approach established in this section provided the theoretical foundation upon which the practical model development process was built.

6 Developing the LAMPD process model

The LAMPD process model was developed through a systematic transformation approach adapted from successful SBCE implementations (Al-Ashaab et al., 2021), proceeding through three stages:

1 *Stage 1 (Company engagement).* Collaborated with Atlas Copco Henrob to understand their current challenges and identify areas for improvement.

2 *Stage 2 (Stage-Gate and SBCE Integration)*. Mapped the company's stage-gate process against the SBCE framework, decomposing phases and reconciling conflicts.

3 *Stage 3 (Lean-Agile PD harmonisation)*. Integrated Scrum and Kanban into the combined model, positioning Scrum ceremonies within LAMPD phases and implementing Kanban visualisation and prioritisation techniques.

6.1 Stage 1: company engagement

Atlas Copco Henrob, a UK-based manufacturer of self-piercing rivets for automotive applications, was selected as the partner organisation. The selection criteria included their established stage-gate PD process, experience with improvement initiatives, and openness to methodology integration. The company's PD process has evolved over five years, incorporating elements from traditional, Agile, and Lean techniques. However, these initiatives were implemented without holistic consideration, creating disconnected improvement approaches rather than a unified methodology. This fragmented implementation hindered transformation towards a Lean-Agile environment, impacting time-to-market and innovation capacity.

Four main improvement areas were identified through structured interviews and process analysis with cross-functional stakeholders. These challenges align with the primary limitations of traditional PD approaches highlighted in the literature, confirming the proposed need for an integrated Lean-Agile approach.

1 *Unclear product definition*: Lack of value alignment, risking wasted resources.

2 *Premature convergence*: Tendency toward early single-solution selection, limiting innovation.

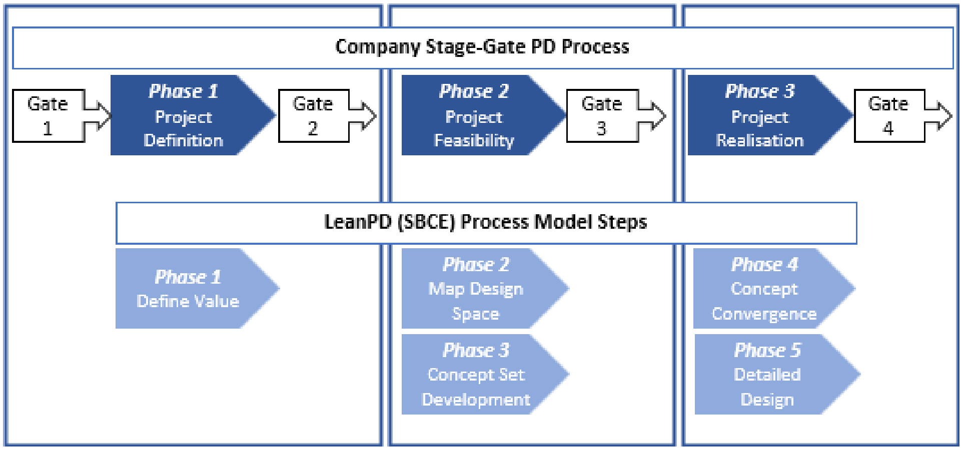
3 *Knowledge management gaps*: Insufficient systematic approach for capturing knowledge.

4 *System integration challenges*: Difficulty integrating subsystems, causing late-stage rework.

6.2 Stage 2: stage-gate and SBCE integration

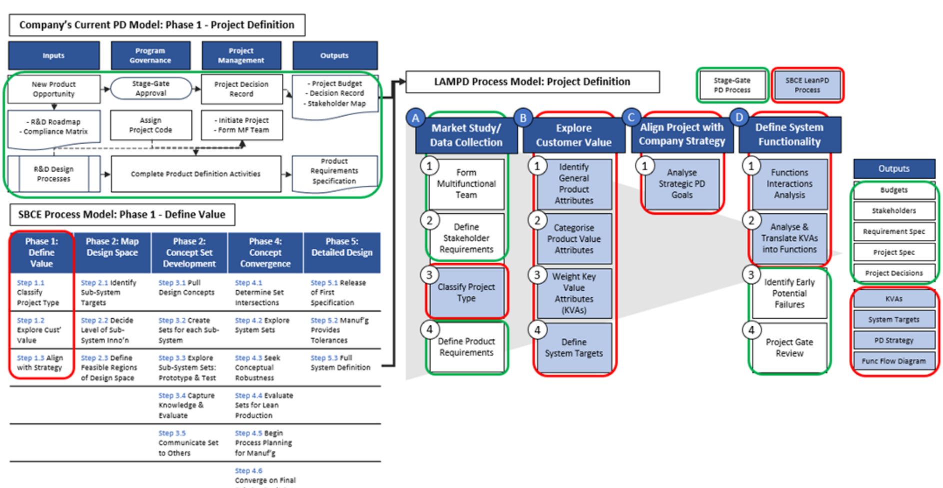
Figure 6 illustrates the company's three-phase stage-gate process integration with Khan's (2012) SBCE process model. Rather than overlaying concepts onto existing processes, this approach systematically reconstructed the process architecture through structured workshops with seventeen domain experts.

Figure 6 Aligning company stage-gate PD phases with lean-PD (SBCE) process model phases (see online version for colours)



Seventeen domain experts with varied functional backgrounds systematically mapped relationships between these frameworks through structured workshops. Integration matrices were developed to evaluate how SBCE's more granular phases could enhance the company's established stage-gate approach while maintaining critical governance checkpoints.

Figure 7 Integrating phase 1 of Atlas Copco's current PD model and phase 1 of the SBCE process model (see online version for colours)



For Phase 1, Product Definition, cross-functional teams first deconstructed existing stage-gate work packages into their fundamental inputs, outputs, and decision gates and visually mapped dependencies between them. Each step from SBCE's 'Define Value' phase was critically evaluated against these mapped elements to identify overlaps, gaps, and complementary functions. The team created integration matrices to aid this mapping, establishing numerical scores to determine how each SBCE element could enhance corresponding stage-gate activities. This analytical mapping revealed that while the company's stage-gate process provided strong governance, it lacked systematic mechanisms for value identification and functional decomposition, precisely the areas where SBCE offered complementary strengths.

This integration resulted in a harmonised flow of activities and knowledge capable of rigorously defining hardware products while blending traditional governance mechanisms with structured exploration and progressive narrowing. This methodical integration approach was replicated across the remaining two development phases. Figure 7 illustrates the resultant harmonised model for the Product Definition Phase with its stage gates and outputs.

6.2.1 Phase 1: project definition

The development project's scope, requirements, and functional outcomes are defined and evaluated in this phase, aligning with the SBCE process model's 'Define Value' phase. The integrated Project Definition phase at Figure 8 comprises four activities:

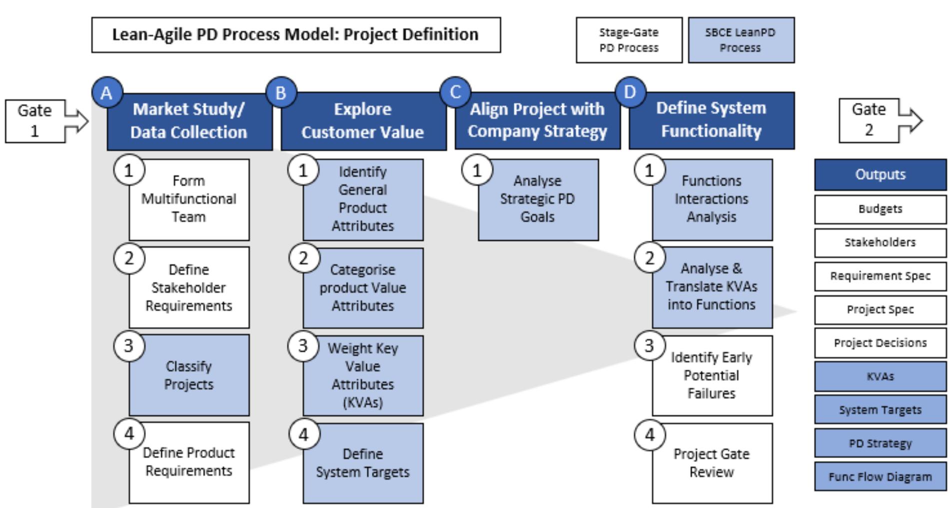
a *Activity A. Market study/Data collection*: Forms the cross-functional team, defines stakeholder and product requirements and classifies the project type.

b *Activity B. Explore customer value*: Identifies general product value attributes, classifies and prioritises them using weighted criteria, and establishes tangible system targets aligned with customer expectations.

c *Activity C. Align product with company strategy*: Evaluate alignment with the firm's long-term goals and examine how the PD process enhances company capabilities and stakeholder relationships.

d *Activity D. Define system functionality*: Translates customer value into key-value attributes, converts these into functional requirements, and analyses interactions between functions at system, subsystem, and component levels.

Figure 8 LAMPD process model project definition phases and activities (see online version for colours)



This phase addresses the first limitation of the existing PD model: the lack of clear product definition and value proposition at the project's outset. Implementing SBCE components provides a structured mechanism for identifying scope, requirements, and intended functional outcomes.

6.2.2 Phase 2: project feasibility

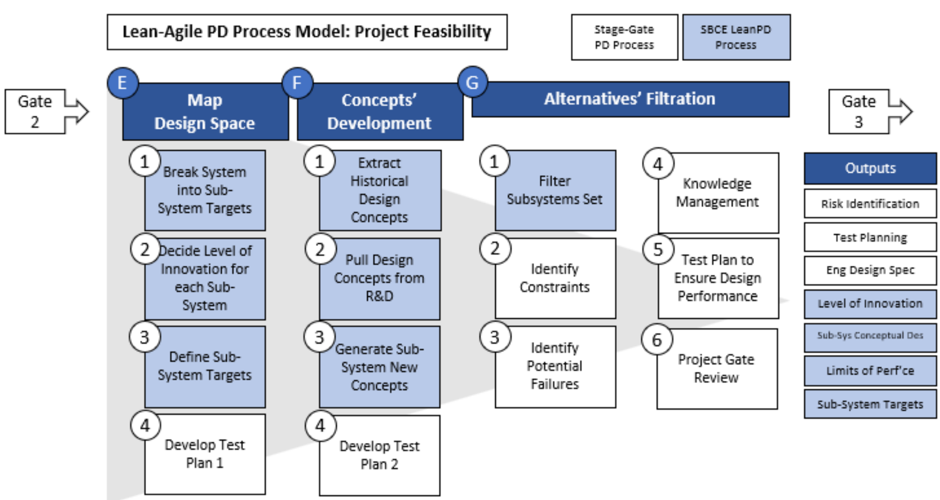
In this phase, the development team evaluates candidate designs based on specifications from Phase 1. It integrates SBCE Phases 2 (Map Design Space) and 3 (Concept Set Development) into the company's existing Project Feasibility activities. The integrated Project Feasibility phase at Figure 9 consists of three key activities:

a *Activity E. Map design space*: Applies systems engineering to decompose the overall system into subsystems and sub-assemblies, categorises components on a predefined innovation scale and establishes specific and measurable targets for subsystems under active development.

b *Activity F. Concepts' development*: Considers historical concepts from relevant previous projects alongside newly developed ideas, evaluates them against defined targets and generates a new set of subsystem concepts for assessment.

c *Activity G. Alternatives' filtration*: Filters candidate designs against previously identified key value attributes while applying design and operational constraints. This critical activity avoids premature rationalisation that could limit innovation potential. Knowledge is continuously captured and categorised throughout this step.

Figure 9 LAMPD process model project feasibility phases and activities (see online version for colours)



This phase incorporates Lean PD principles by systematically decomposing and categorising systems while evaluating historical and new concepts. This addresses two improvement opportunities: encouraging comprehensive option consideration and enhancing organisational learning through structured knowledge management.

6.2.3 *Phase 3: project realisation*

In the final phase, subsystems proposed in Phase 2 are further refined, evaluated against criteria, and merged to propose an optimised whole-product solution. It integrates SBCE Phases 4 (Concept Convergence) and 5 (Detailed Design) into the company's existing Project Realisation activities. The integrated Project Realisation phase at Figure 10 consists of three key activities:

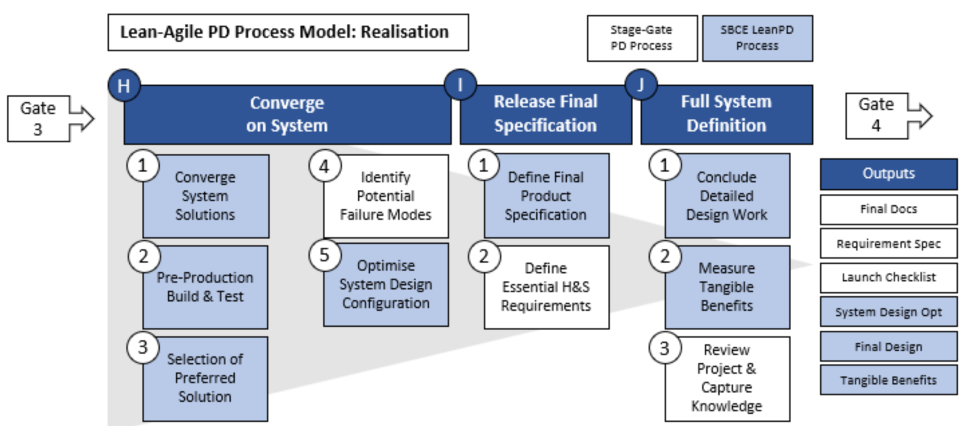
a *Activity H. Converge on system*: Involves extensive integration of the product's subsystems into potential configurations, evaluating these combinations against cost, quality, feasibility, risk, and performance criteria and testing preferred groupings.

b *Activity I. Release final specification*: Formally documents the product's design specification after reaching a consensus on the final design, avoiding premature declaration that could lead to costly modifications.

c *Activity J. Full system definition*: Finalises the system definition after obtaining approval from operations, procurement, and quality teams, allowing further refinement, validation, and qualification of design solutions for release.

This final phase embeds Lean PD principles into the conventional PD process, prioritising value creation, final design specifications, and manufacturing readiness. The structured convergence of multiple candidate subsystems into an optimised solution addresses the final improvement opportunity identified in the existing model.

Figure 10 LAMPD process model project realisation phases and activities (see online version for colours)



6.3 *Stage 3: Lean-agile PD harmonisation*

In the third stage of transformation, three complementary Agile elements were integrated within the harmonised stage-gate and SBCE model, each serving distinct but interconnected roles. Rather than implementing Agile practices as standalone techniques, the integration approach focused on embedding Agile elements at strategic points to enhance knowledge flow and adaptive capacity without sacrificing structural integrity.

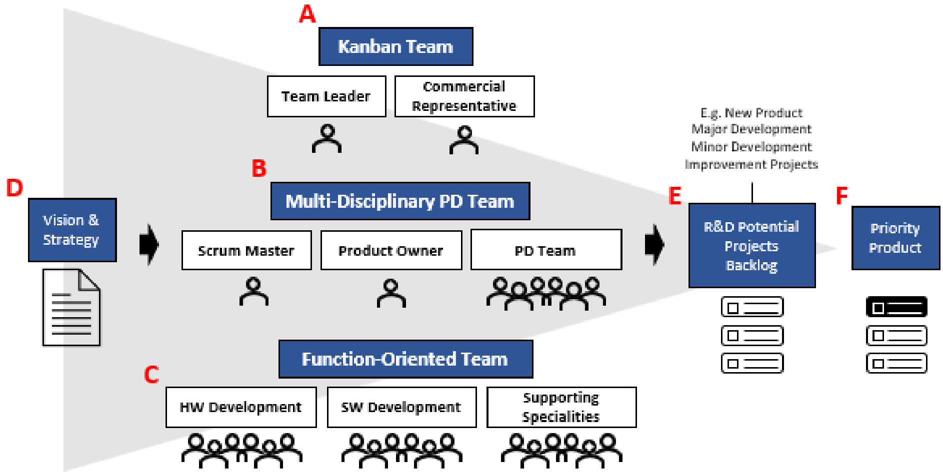
1 *Scrum as the governing framework*: Scrum was established as the primary governance mechanism across all LAMPD phases, building on established integration approaches. Unlike previous attempts that merely added Scrum ceremonies to stage-gate processes, our integration mapped specific Scrum events to corresponding SBCE activities, ensuring purpose alignment rather than procedural overlay. Scrum provides a time-bounded structure for maintaining development momentum through sprint cycles, reviews, and retrospectives, overcoming hardware development's challenge of maintaining progress despite longer prototyping lead times. Practical modifications were made to standard Scrum ceremonies; sprint planning was expanded to include knowledge gap identification, and reviews were enhanced with structured knowledge capture mechanisms from SBCE practice. These adaptations ensured Scrum's iterative cadence supported rather than conflicted with SBCE's knowledge-based development approach.

2 *Kanban for prioritisation, visualisation, and work management*: Kanban methods were integrated, serving three specific purposes:

- *Product and project prioritisation*: A Kanban system (Figure 11) facilitates selecting products for development from the project pool, with a dedicated team (team leader and commercial representative (**A**) collaborating with a multidisciplinary PD team (**B**) and function-oriented groups (**C**) to evaluate potential products against company vision (**D**) and prioritise projects (**E**) before selecting the highest priority product for development (**F**).
- *Workflow visualisation*: Kanban boards visualise design sets, processes, and knowledge flows, making complex SBCE activities transparent across functional boundaries. This visualisation directly addresses the knowledge management gaps identified in Stage 1.
- *Work-in-progress (WiP) limitation*: WiP limits prevent the overloading of teams and resources, ensuring focused execution on critical tasks while maintaining the breadth of exploration required in set-based design.

4 *Agile principles as mindset and cultural drivers*: The 12 Agile Principles were selectively harmonised with specific steps within each LAMPD phase, serving as the philosophical foundation governing the development approach, team interactions, and organisational culture. These principles drive the mindset transformation necessary for successful implementation, encouraging adaptability, customer focus, and continuous improvement – essential cultural shifts for organisations transitioning from traditional approaches. The harmonisation process used principle mapping to guide where specific Agile principles would have maximum impact within SBCE. For example, Agile Principle 3 (Deliver working software frequently) was adapted to 'Deliver validated knowledge frequently' and embedded within SBCE's concept development activities.

Figure 11 Selection of prioritised products for development using Kanban (see online version for colours)

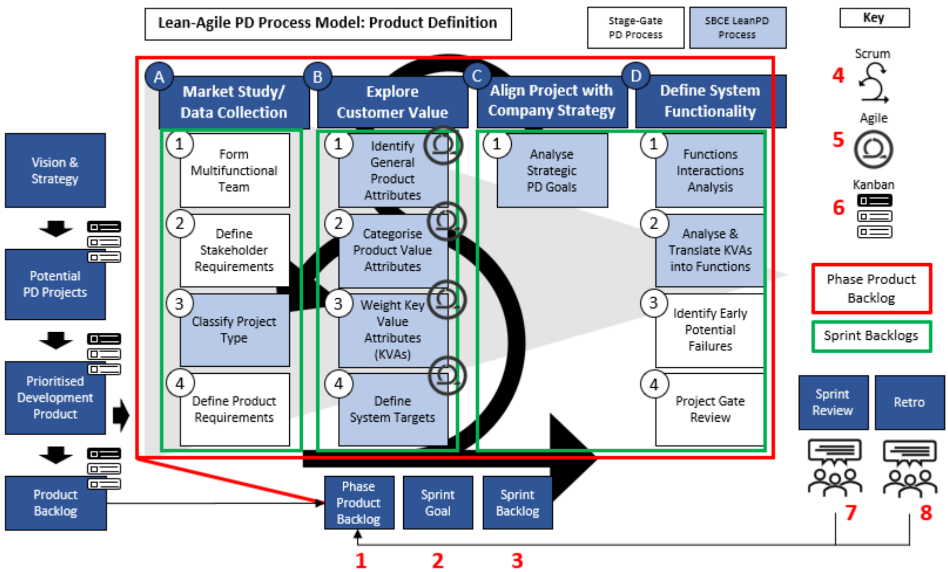


This integration addresses critical limitations each approach faces in hardware development when used individually. Scrum struggles with hardware's longer prototyping cycles, Kanban lacks systematic design exploration mechanisms, and Agile Principles need implementation structures. Embedding these elements within the SBCE model enables teams to maintain Scrum's iterative rhythm and SBCE's methodical design exploration, supported by Kanban's visualisation and Agile Principles' cultural foundation. This combination addresses hardware development's unique challenges, which require more structured approaches than software development while enhancing knowledge management by uniting Kanban's workflow visualisation with SBCE's knowledge capture systems to create a continuous improvement cycle.

6.4 Final LAMPD process model

Figure 12 illustrates the final synthesis of Scrum, Kanban, stage-gate, and SBCE within the Product Definition phase of the LAMPD process model. The totality of activities across the three phases collectively form the Product Backlog as defined in Scrum, beginning with Phase 1 activities and evolving as phases conclude and transition. When planning each sprint, the team pulls prioritised tasks from the Product Backlog to form the Phase Product Backlog **(1)** (shown by the red box), establishes a specific goal for the time-boxed period **(2)**, and creates Sprint Backlogs **(3)** (outlined by green boxes). This example demonstrates a Phase Product Backlog feeding three sequential Sprint Backlogs. During execution, the Scrum framework governs development activities **(4)**, providing a structured cadence for daily collaboration and progress tracking, while Agile Principles **(5)** shape the team's mindset and approach, and Kanban's work-in-progress limitations **(6)** ensure focus on high-value tasks without overwhelming capacity.

Figure 12 Harmonisation of Kanban, scrum, and agile principles and artefacts into the project definition phase of the LAMPD process model (see online version for colours)



A review is conducted at each sprint's end to assess the value added and allow stakeholders to provide feedback **(7)**. Following this, a sprint retrospective identifies ways to improve future sprints and development direction **(8)**. This cyclical approach helps continuously refine the product and PD process until all tasks are completed. At this point, a gate review transitions the project to the next LAMPD phase. This integrated approach enables teams to experience the benefits of both methodologies while maintaining a structured yet flexible development process.

7 Expert evaluation of the LAMPD process model

All PD approaches have merits, and combining multiple approaches does not necessarily deliver an optimised combination of benefits. To explore whether the new combined LAMPD would enable better outcomes, we conducted an expert evaluation through a survey of practitioners. The survey asked respondents whether the new model would deliver the 37 benefits researchers claimed to have experienced in implementing Lean PD and Agile case study.

A five-point Likert scale (strongly agree, agree, not sure, disagree, strongly disagree) standardised responses and simplified data analysis. Before conducting the survey, the R&D department at Atlas Copco Henrob was trained to understand the new LAMPD Process Model approach and its future implementation. The survey was shared with 25 members of the R&D department. Seventeen respondents completed the survey, corresponding to a 68% response rate. These included three engineering managers, four senior engineers, and 10 engineers, with 10 respondents having over 10 years of professional experience in engineering.

The survey methodology enabled us to assess practitioners' perceptions of the model's potential benefits before full implementation, providing valuable insights into expected outcomes while identifying areas of uncertainty that might require attention during rollout. This approach aligns with the expert evaluation phase of the DRM framework described in our methodology section, allowing for model refinement based on practitioner feedback before completing implementation testing.

8 Evaluation results

Expert evaluation revealed strong organisational readiness for LAMPD, with over 75% agreement on 34 of 37 potential benefits. This analysis indicates practitioners' recognition that LAMPD addresses specific pain points in current PD approaches. The findings are significant given participants' extensive experience in both methodologies, suggesting successfully bridging perceived gaps.

Human factors (communication, collaboration, knowledge sharing) emerged as primary themes rather than process efficiency metrics typically associated with Lean. While traditional Lean implementations emphasise process optimisation and waste reduction, practitioners anticipated the most significant benefits in team dynamics and information flow. This observation highlights how engineers perceive PD challenges as complex socio-technical systems where human interaction significantly impacts outcomes. Thematic analysis identified nine core benefit categories demonstrating advantages unattainable through either approach alone:

1. *Enhanced communication*: Combining Agile's face-to-face communication with SBCE's knowledge-sharing frameworks creates transparency across functional boundaries.
2. *Time/cost benefits*: SBCE's front-loaded exploration reduces early uncertainty while Agile's sprint cycles maintain momentum, minimising late-stage changes.
3. *Process control*: Kanban visualisation with SBCE's convergence process creates transparent decision-making while maintaining rigorous evaluation.
4. *Risk management*: Parallel risk assessment across multiple design alternatives with regular re-evaluation addresses risks at subsystem intersections.
5. *Innovation support*: Protected innovation spaces balance methodical exploration with adaptability within physical constraints.
6. *Knowledge management*: Systematised knowledge generation and reflection points integrate learnings where technical knowledge might remain tacit.
7. *Quality improvement*: Earlier verification while maintaining structured convergence allows more comprehensive design space exploration.
8. *Flexibility*: Set-based exploration with Agile reprioritisation mechanisms addresses requirement changes where late modifications are costly.
9. *Complexity management*: SBCE's systematic decomposition with Agile's iterative approach manages dependencies while enabling parallel component development.

Areas of uncertainty included ease of adoption (35%), documentation reduction (41%), and iteration reduction (29%). These reflect practitioners' realistic assessment of change management challenges, the tension between Agile's minimal documentation and hardware development's traceability requirements, and the inherent iterative nature of complex PD. The unanimous positive sentiment toward 33 benefits indicates a strong alignment between theory and practitioner expectations, suggesting LAMPD effectively addresses key pain points while maintaining the core benefits of both methodologies.

9 Discussion

The development and evaluation of the LAMPD process model successfully addressed our research objectives. Examining Lean PD and Agile PD implementations revealed complementary strengths confirmed by practitioners identifying benefits that bridge hardware and software development divides. Our harmonisation exercise demonstrated minimal conflicts between approaches, with 33 of 37 benefits achievable through integration, substantiated by practitioner agreement across multiple dimensions. LAMPD unifies SBCE's structured guidance with Agile's flexibility through systematic transformation. Rather than simply overlaying methodologies and expecting harmony, our approach decomposed and reconstructed process elements to address specific improvement areas while maintaining governance integrity. Expert evaluation suggests superior outcomes compared to individual implementations, particularly in communication, knowledge sharing, and risk reduction. Notably, human factors emerged as primary anticipated benefits, revealing practitioners view this integration as transformative for team collaboration.

While previous research has explored Lean-Agile integration in software and healthcare contexts, LAMPD explicitly addresses hardware development's unique challenges. Unlike Ni et al.'s (2020) framework, our approach comprehensively integrates SBCE, Scrum, and Kanban. Compared to Sommer et al.'s (2015) Agile-stage gate hybrids, our model more thoroughly incorporates Lean PD principles with specific knowledge management mechanisms.

The model has important theoretical implications by challenging traditional methodological dichotomies, extending set-based engineering theory, and contributing to contingency theory through context-tailored integration. Practically, it provides organisations with a framework for enhancing efficiency in hardware development by combining Lean PD's knowledge capture with Agile's iterative development. The positive practitioner response suggests benefits beyond process improvement, potentially building organisational capabilities and competitive advantages through enhanced innovation and cross-functional collaboration. Despite promising findings, implementation challenges remain. Uncertainty around documentation and iteration efficiency highlights the need for careful planning and training to realise LAMPD's full benefits.

10 Limitations

This research provides valuable insights into integrating Lean and Agile methodologies; however, several limitations must be acknowledged that provide context for interpreting our findings and highlight opportunities for future research. First, the LAMPD model lacks practical validation through full implementation in a real-world PD cycle. While expert evaluation indicates potential benefits, it represents theoretical assessment rather than empirical evidence. Complete validation would require implementation across multiple projects with measured outcomes against established metrics. The authors will address this in subsequent research tracking the full implementation of an industrial project.

Second, model development occurred with a single manufacturing company, potentially limiting generalisability. The company's familiarity with Lean and Agile concepts may have influenced the positive reception of the integrated model. Applying LAMPD in organisations with different maturity levels might yield different implementation challenges or benefits. Third, expert evaluation involved 17 R&D professionals from one organisation. While providing valuable insights, a broader assessment across multiple organisations would strengthen findings and better identify implementation challenges in diverse contexts. This homogeneity may have introduced bias and significantly impacted the generalisability of findings, particularly regarding the nine benefit categories identified. Different PD cultures and maturity levels may experience other benefits or challenges when implementing LAMPD.

Fourth, the model may contain industry-specific elements requiring adaptation beyond manufacturing contexts. Hardware development's unique constraints shaped the model's design, potentially limiting direct applicability to other domains without modification. Finally, the harmonisation process involved subjective judgements in mapping principles and resolving conflicts. Different interpretations or alternative approaches might yield different integration models. This inherent subjectivity should be acknowledged when considering the model's universality. These limitations provide direction for future studies to build upon this work.

11 Recommendations

Based on these findings, several recommendations can be made for successfully implementing the LAMPD approach and future research directions.

11.1 Implementation recommendations

For successful LAMPD implementation, organisations should adopt five key strategies. First, tailor the model to their context by considering organisational culture, project complexity, and team dynamics, ensuring alignment with existing processes. Second, invest in comprehensive training programmes that educate team members on Agile and Lean principles, emphasising their integrated nature to prevent resistance and enhance collaboration. Third, cross-functional teams that leverage diverse perspectives and expertise should be established, creating a collaborative environment that fully utilises LAMPD's comprehensive approach.

Fourth, develop clear metrics to measure LAMPD's impact on product development outcomes, capturing efficiency, time-to-market, quality improvements, and team satisfaction to provide a holistic view of effectiveness. Finally, continuous improvement should be embraced as a core philosophy, establishing regular review sessions and feedback loops to assess implementation progress and make necessary adjustments, reflecting the iterative nature that underpins both Lean and Agile methodologies.

11.2 Future research directions

Future research directions should include pilot implementations across various organisations to provide practical examples, focusing on the ongoing Atlas Copco Henrob implementation where metrics such as cycle time, design iterations, knowledge capture, and team satisfaction are tracked. Comparative analyses across different industries will also help identify contextual factors influencing LAMPD's effectiveness. At the same time, studies on scalability should investigate applications to more complex projects, focusing on specific challenges and best practices for larger implementations. Longitudinal studies tracking LAMPD's long-term impact will be essential to understanding its sustainability and evolution over time, complemented by investigations into how organisational culture influences adoption success and what specific interventions might facilitate better cultural alignment with the integrated methodology.

12 Conclusion

This research presented a combined lean and agile model for product development (LAMPD) that integrates these methodologies for hardware contexts. Through systematic harmonisation of principles and practices, we developed a structured framework leveraging complementary strengths from both approaches. The LAMPD model was implemented in a manufacturing case study and evaluated by industry practitioners, who strongly endorsed its benefits in communication, knowledge management, and risk reduction. The model addresses a significant gap in PD literature by providing organisations with practical mechanisms to enhance efficiency and adaptability in hardware development. Its theoretical contribution challenges traditional methodological dichotomies while extending set-based engineering theory into more flexible development contexts.

Our approach to methodology transformation represents a significant contribution beyond the model itself. Rather than merely overlaying new concepts onto existing processes, we systematically decomposed and reconstructed the process architecture to create a unified framework that maintains the integrity of component approaches while addressing their limitations. This builds upon established SBCE implementation approaches while incorporating Agile principles to achieve lean transformation. As organisations face increasing competitive pressures and supply chain volatility, integrated approaches like LAMPD become increasingly valuable. Future research will test the model in diverse contexts and extend it to cover the complete product lifecycle, including subsystem and component levels.

Conflicts of interest

All authors declare that they have no conflicts of interest.

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