

KNOWLEDGE MANAGEMENT IN THE DESIGN OF A COMPLEX INDUSTRIAL PRODUCT

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Abstract: Digital transformation increases the complexity of industrial product design by amplifying information flows, interdependence and coordination requirements between multidisciplinary engineering teams. In this context, knowledge management (KM) represents a critical organizational capability for capturing technical expertise, structuring information and ensuring efficient collaboration throughout the entire product lifecycle. This paper examines KM in the design of complex industrial products, with a particular focus on Product Lifecycle Management (PLM) systems and organizational conditions that influence knowledge reuse and decision consistency. An exploratory study combines a focused literature review with industrial evidence collected via semi-structured interviews (12 experts in design, validation, quality and PLM administration) and a survey of 48 practitioners from automotive and discrete manufacturing functions. The collected qualitative and quantitative data were synthesized using the Ishikawa cause-effect diagram to systematically identify and classify the root causes of inefficiencies related to knowledge flows in industrial product design. The results highlight that information fragmentation across teams, insufficient codification of tacit expertise and persistent communication barriers are the main factors limiting performance, leading to duplicated work, delays and decision-making inconsistencies. When supported by standardized capture routines and continuous training, PLM improves transparency, traceability and error reduction. The paper proposes an integrated improvement approach combining PLM-linked collaboration, formalized knowledge capture at project gates, and leadership-supported cultural change.

Key words: knowledge management; complex industrial products; industrial engineering; PLM; Ishikawa diagram; digital transformation.

NOMENCLATURE

KM – Knowledge Management;
PLM – Product Lifecycle Management;
ERP – Enterprise Resource Planning;
CAD – Computer-Aided Design;
AI – Artificial Intelligence;
KPI – Key Performance Indicator;
FMEA – Failure Mode and Effects Analysis.

1. INTRODUCTION

Knowledge management (KM) has become a central research theme in industrial engineering because organizational performance increasingly depends on the ability to create, capture, structure, share and reuse knowledge across complex product development processes. In modern industrial contexts, knowledge is not limited to documented information; it also includes tacit expertise embedded in individuals and teams, as well as routines and practices that enable problem solving under uncertainty. A key insight emphasized by

the literature is that effective KM requires a balance between individual expertise and collective organizational mechanisms such as codification practices, governance and learning routines [1, 8]. This socio-technical perspective is particularly relevant for complex product design, where multiple disciplines must converge under strict constraints of cost, quality and timing.

A recurrent theoretical foundation in KM research is the distinction between tacit and explicit knowledge and the organizational challenge of converting experience into reusable forms. Brătianu (2015) argues for a multidimensional view in which knowledge is dynamic and context-dependent, shaped by human cognition, organizational culture and managerial decisions [1]. In industrial organizations, tacit knowledge is expressed through engineering judgement, informal heuristics and experiential know-how acquired during design iterations, validation activities and manufacturing ramp-up. Converting tacit knowledge into explicit representations—lessons learned, design rationale, best practices, standardized templates or decision logs—enables reuse, consistency and training. Without systematic conversion, organizations tend to repeat the same mistakes across projects, especially when teams change, suppliers rotate, or programs overlap.

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From a technological perspective, Product Lifecycle Management (PLM) platforms have evolved into central infrastructures for managing product definition, configuration control and traceability across lifecycle stages. Stark (2023) describes PLM as an integration backbone that links engineering artifacts, maintains version control and supports collaboration between design, manufacturing, quality and supply-chain stakeholders [2]. By operating as a single source of truth, PLM can reduce information overload, increase transparency and support evidence-based decisions. However, PLM effectiveness depends on how well it is integrated with organizational processes, governance rules and user adoption. In practice, PLM capabilities are often underused, leading to fragmented repositories, duplicated documentation and weak traceability of decisions.

The link between knowledge and innovation is reinforced by research on dynamic capabilities and innovation networks. In networked industrial environments, organizations must continuously reconfigure knowledge resources to adapt to technological change, regulatory constraints and market pressure [8]. This capability to sense, integrate and transform knowledge becomes critical for complex products, where architecture decisions and subsystem interactions can generate cascading effects across the lifecycle. Moreover, knowledge creation and diffusion increasingly occur across organizational boundaries – partnerships, suppliers and global engineering centers – raising the importance of interoperability and shared understanding [7]. Lifecycle standards provide an operational backbone for how organizations structure engineering activities and govern information flows. ISO/IEC/IEEE 15288 specifies system life-cycle processes, including management and support processes connected to information governance, configuration management, verification/validation and organizational learning [11]. Aligning KM initiatives with lifecycle process frameworks helps embed knowledge capture into formal milestones rather than treating it as an ad-hoc activity, improving consistency and traceability.

Recent works highlight the role of advanced digital technologies – collaborative platforms, artificial intelligence (AI) and knowledge graphs – in supporting decision making and improving knowledge transfer. Blind and Kromer (2025) discuss how standards and research inputs shape digital ecosystems [6], while Wu and Chen (2019) emphasize mechanisms that facilitate learning and transfer [10]. In manufacturing contexts, AI-enabled search, automated tagging and recommendation of reusable solutions can augment organizational memory and reduce time to access relevant information, including knowledge-graph-based approaches for planning and reuse [5]. Nevertheless, technology remains an enabler: without clear processes, incentives and training, digital tools may reinforce fragmentation rather than resolving it.

Despite conceptual and technological maturity, many industrial organizations still struggle to operationalize KM consistently in complex product design. Common difficulties include fragmented information across tools,

incomplete codification of expertise and persistent communication barriers, especially in cross-functional and international contexts. The central gap lies in aligning PLM/ERP infrastructures with standardized knowledge capture routines, training programs and leadership practices that nurture a culture of knowledge sharing. This gap motivates the present exploratory study and supports the use of explicit causal modelling (Ishikawa) to identify root causes and prioritize integrated improvement actions across People, Methods, Information, IT, Environment and Management.

The design of complex industrial products requires continuous coordination between technical, organizational and informational processes, under uncertainty and constraints on cost, quality and timing. As products integrate mechanical, electrical, software and service elements, engineering teams generate large volumes of heterogeneous data and depend on tacit expert know-how to resolve non-standard, cross-disciplinary problems. When such knowledge is not captured and reused systematically, organizations face repeated errors, duplicated work, slower decision-making and a higher risk of late changes or quality incidents.

2. PROBLEM DESCRIPTION

Industrial evidence increasingly shows that the bottleneck is rarely the lack of information, but rather the lack of coherence and traceability: data are fragmented across tools and teams, assumptions and rationales are not documented, and lessons learned remain local to projects or individuals. Communication barriers – created by functional silos, distributed sites and varying practices – reduce the efficiency of interdisciplinary collaboration and weaken feedback loops between design, manufacturing and validation. Consequently, knowledge management becomes a strategic lever because it provides mechanisms for capturing, structuring, sharing and valorizing experience at both individual and organizational levels. Many initiatives remain either technology-centric (focused on repositories) or process-centric (focused on procedures) and fail to connect people, methods and tools into a consistent operating model. PLM systems can provide a structured backbone for product information, yet their benefits depend on disciplined processes, governance and user capabilities.

This study targets complex product development in industrial engineering settings, with direct applicability to automotive and discrete manufacturing organizations where PLM/ERP/CAD ecosystems are widely deployed. The paper's originality is threefold:

- (i) it combines qualitative and quantitative evidence on knowledge-related issues during product design;
- (ii) it adapts the Ishikawa cause-and-effect logic to model inefficiencies across People, Methods, Information, IT, Environment and Management; and
- (iii) it translates the causal model into actionable directions that integrate digital integration, standardized knowledge capture routines and leadership-supported cultural change. These contributions support knowledge reuse and design performance.

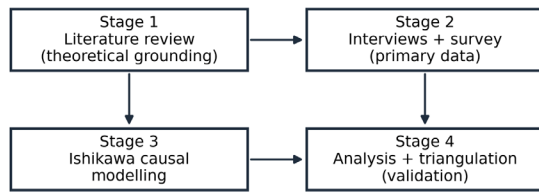


Fig. 1. Research design (exploratory) and methodological stages.

3. RESEARCH STAGES AND METHODS

3.1. Research design and overall approach

The research follows an exploratory design suitable for complex socio-technical phenomena that are context dependent and difficult to quantify directly. The methodological structure comprises four stages: theoretical grounding through literature review; primary data collection through semi-structured interviews and a structured survey; causal modelling using an Ishikawa diagram; and analysis and validation through triangulation [10]. This structure allows the study to capture strategic and operational insights and translate empirical evidence into an actionable diagnostic model.

Figure 1 illustrates the overall research design and the sequence of methodological stages.

Stage 1 – Theoretical grounding: A focused review was carried out to identify key concepts and operational mechanisms related to knowledge management, tacit – explicit conversion, PLM-enabled collaboration and digital technologies supporting knowledge reuse [1, 2, 5]. This stage also supported the identification of recurrent challenges described in the literature, such as fragmented information environments, weak traceability of decisions, limited reuse of expertise and barriers to cross-functional collaboration [1, 2]. The outputs of this stage were used to define the analytical lens and to ensure that the empirical investigation addresses relevant constructs rather than isolated operational symptoms.

Stage 2 – Primary data collection: Data collection was designed to balance depth and breadth. Semi-structured interviews were used to capture rich, contextual insights from experienced practitioners, while the survey was used to quantify perceptions across a wider range of technical roles. This combination supports methodological triangulation in order to verify the convergence of qualitative and quantitative aspects, strengthening the credibility of the interpretation [10].

Stage 3 – Causal modelling: The Ishikawa (fishbone) diagram was selected as the synthesis tool because it supports structured identification of root causes and makes interdependencies explicit, which is essential for diagnosing socio-technical problems typical in industrial engineering [12, 13]. The modelling step consolidates evidence from interviews and the survey into a coherent causal structure, which supports prioritization of improvement directions rather than presenting findings as disconnected lists.

Stage 4 – Analysis and validation: The final stage integrates thematic findings and survey trends, using triangulation to validate which issues are robust across sources and which are context-specific. Validation is treated as a process of strengthening interpretability and coherence rather than forcing perfect agreement across

methods, in line with standard qualitative research practice [10].

3.2. Target group, sampling and data collection

The targeted group consists of professionals involved in complex industrial product design and development, particularly in organizations where PLM/ERP/CAD ecosystems are used to manage product data, configuration and collaboration. The selection is justified by the role of knowledge flows in complex projects, where decisions and engineering rationale must be coordinated across disciplines, sites and lifecycle functions [2].

Two complementary participant groups were selected to ensure relevance and validity. First, 12 experts were interviewed, with strategic roles in product design, validation, quality management and PLM administration. Selection criteria included experience in complex industrial projects, exposure to cross-functional collaboration and availability for detailed interviews. Second, a survey was applied to 48 respondents from technical functions (process and production engineers, product managers, systems engineering specialists and PLM implementation experts) in automotive and manufacturing environments. The sampling approach was purposive, aiming to maximize functional diversity and obtain a realistic picture of knowledge practices in PLM/ERP/CAD ecosystems.

Semi-structured interviews represented the main qualitative instrument. They were designed to explore how knowledge is captured, shared and reused, how digital tools are used in day-to-day engineering work, what barriers occur in collaboration, and which organizational conditions support or limit the effectiveness of knowledge management practices. This format allowed the interviewer to probe for example, clarify implicit assumptions and identify latent practices that are often missing from formal documentation [1, 2]. The survey complemented the interviews by providing a structured view of perceptions from a larger number of respondents. It included closed-ended and multiple-choice questions to assess perceived efficiency of information access, knowledge reuse and the availability of integrated collaborative platforms. This instrument was aligned with the interview themes and the theoretical framework, enabling cross-checking between qualitative findings and quantitative tendencies [1, 2, 3].

3.3. Data analysis, causal synthesis and methodological validation

Interview data were transcribed and analyzed through thematic coding (initial, axial and selective), allowing patterns and relationships to emerge across participants. This approach supports systematic identification of recurring themes, while maintaining sensitivity to context and meaning. The coding process was oriented toward discovering both technical and organizational drivers of inefficiency, including information fragmentation, insufficient codification of tacit expertise, communication barriers and underutilization of PLM/ERP capabilities [1, 2]. Themes were then consolidated into higher-level categories consistent with the research objectives and used to inform the causal modelling step.



Fig. 2. Data collection, analysis and causal synthesis workflow.

Survey results were analyzed using descriptive summaries to identify dominant perceptions regarding access to critical information, reuse of expertise and the presence of collaborative digital support. Quantitative patterns were interpreted in relation to qualitative themes to assess convergence. When survey trends reinforced interview findings, the evidence was treated as more robust; when divergence appeared, it was interpreted as a potential indicator of role-dependent perspectives or organizational maturity differences, rather than as an error [10].

Figure 2 summarizes the data collection and synthesis workflow used to integrate qualitative and quantitative evidence into the Ishikawa causal model.

The Ishikawa diagram served as an integrative synthesis tool. Causes identified from interviews and survey responses were grouped into six categories adapted for the industrial engineering context: People, Methods, Information (Materials), IT (Equipment), Environment and Management [12]. This categorization supports a comprehensive view of root causes by ensuring that both technical and organizational dimensions are considered simultaneously. The resulting causal structure provides a clear rationale for improvement directions, linking observed problems to actionable levers such as digital integration, standardized capture routines and capability building.

Validation relied on methodological triangulation, combining interviews and survey evidence to strengthen the credibility of interpretations, while the literature review provided a theoretical plausibility check [1, 2, 5]. Limitations are acknowledged transparently: the study is exploratory and uses moderate sample sizes, limiting statistical generalization; however, the design supports analytical generalization by offering a transferable diagnostic framework applicable to similar complex product development environments.

4. RESULTS AND DISCUSSION

Findings are reported for each data source and then synthesized through the causal model. Overall, the evidence indicates that knowledge-management inefficiencies stem from both technical fragmentation (tools and data) and organizational fragmentation (roles, communication and governance), producing delays, duplicated work and rework loops in complex product design. In practice, these inefficiencies appear as repeated clarification cycles, multiple versions of the same deliverable, delayed validation readiness, and time-consuming searches for “the right information” across different repositories. Such effects are amplified in multidisciplinary environments where decisions require alignment between design, validation, manufacturing and quality functions, and where the absence of traceable knowledge quickly propagates into late changes and avoidable iterations.

4.1. Expert interviews ($n = 12$)

Expert interviews ($n = 12$) were thematically coded into four dominant challenges that together accounted for approximately 90% of all coded statements, with the remaining ~10% distributed across several low-frequency issues.

First, information fragmentation across teams and repositories emerged as the most salient challenge (~30% of coded statements). Participants described inconsistent storage locations, parallel documentation practices, and limited traceability of decisions, which create uncertainty regarding which dataset or document version should be considered authoritative. This fragmentation increases coordination costs because engineers must spend time reconciling contradictory inputs, re-checking assumptions and rebuilding design rationale that should have been readily available. Additionally, when information is dispersed across tools, it becomes difficult to reuse solutions from prior projects or to ensure continuity when team members change roles, sites or projects.

Second, insufficient codification of tacit expertise (~25%) was strongly linked to the incomplete implementation and inconsistent use of standardized routines for capturing design rationale, lessons learned, and validation feedback. Experts emphasized that many critical decisions remain embedded in individual experience or informal communication channels, rather than being translated into explicit knowledge assets that can be reused. As a result, knowledge tends to be “recreated” repeatedly, especially under time pressure, and organizations remain dependent on a small number of key individuals. This issue is not purely technological: even when PLM platforms exist, codification requires governance rules (what must be captured, when and by whom) and consistent templates for documenting rationale, trade-offs and validation outcomes.

Third, persistent communication barriers (~20%) were associated with functional silos, distributed sites, and heterogeneous terminology across disciplines, reducing the speed and quality of decision-making. Interviewees described situations where teams interpret requirements differently, where feedback from validation is not sufficiently contextualized for design teams, and where local practices limit the transfer of lessons learned across projects. Communication barriers also manifest as delayed escalation of issues and incomplete alignment on problem definitions, which increases the risk of solving the “wrong problem” or implementing local optimizations that create downstream inconsistencies.

Finally, suboptimal use of PLM/ERP capabilities (~15%) indicated that digital tools are often available but not configured, integrated, or adopted in ways that effectively support knowledge reuse and collaboration. Experts noted that the presence of PLM does not automatically guarantee a coherent knowledge flow: access rights may be inconsistent, workflows may not enforce mandatory documentation, and interfaces between PLM, ERP and CAD may be incomplete. Consequently, teams revert to informal tools (emails, local folders, spreadsheets), reinforcing fragmentation and weakening traceability. Importantly, interviewees framed this challenge as a socio-technical gap:

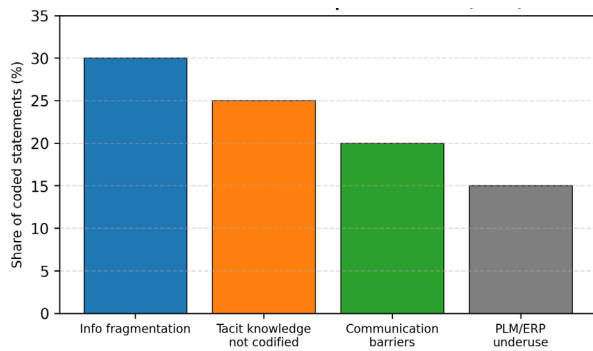


Fig. 3. Distribution of themes derived from expert interviews regarding knowledge-management issues during product design.

technology must be supported by training, clear governance and leadership involvement to ensure disciplined usage and shared practices.

Figure 3 summarizes the distribution of coded themes derived from interviews. This distribution supports the interpretation that the primary constraints are not isolated technical defects, but systemic weaknesses in how knowledge is captured, structured and circulated across teams. The results therefore justify a causal synthesis approach (Ishikawa) to map interdependencies and to translate the identified barriers into integrated improvement directions that combine process standardization, digital integration and organizational change

4.2. Survey results ($n = 48$)

Survey results ($n = 48$) provide a quantitative view that corroborates the qualitative findings and adds clarity regarding how widespread the perceived issues are among technical practitioners. Overall, the survey indicates that knowledge-management inefficiencies are experienced not as isolated exceptions, but as recurring constraints that affect day-to-day engineering work, particularly when teams need rapid access to reliable product information and consistent reuse of validated solutions. The quantitative results also help distinguish between problems linked to information availability, problems linked to reuse practices, and problems linked to collaboration infrastructure—three dimensions that frequently interact in complex product design environments.

A large majority of respondents reported only partially efficient access to critical information (72%), suggesting that friction persists in retrieving the right data at the right time. This result implies that engineers often face delays caused by searching across multiple sources, validating which version is up to date, or requesting clarifications from colleagues rather than relying on a stable and transparent knowledge base. In practical terms, “partially efficient access” typically translates into additional coordination time, repeated checks of assumptions, and increased risk that decisions are made using incomplete or outdated information – factors that can trigger rework loops later in the project lifecycle.

Difficulties in reusing existing expertise were reported by 65%, indicating that organizations still rely

heavily on informal networks – such as personal contacts, ad-hoc discussions or local “know-who” dependencies – rather than on institutionalized knowledge assets that can be systematically retrieved and applied. This finding is important because it suggests that even when experience exists within the organization, it is not consistently translated into reusable artifacts such as lessons learned, validated design patterns, or decision rationale captured in a standardized form. As a result, teams may repeatedly solve similar problems, especially under time pressure, and the organization remains vulnerable to knowledge loss when key individuals change roles or leave projects.

Furthermore, 58% signaled the absence of integrated collaborative platforms, pointing to gaps between PLM as a backbone system and day-to-day collaboration practices. This result does not necessarily mean that PLM is missing; rather, it suggests that collaboration workflows are not integrated sufficiently with PLM-based traceability. In many industrial contexts, teams use parallel channels (email threads, shared folders, spreadsheets, messaging tools) to coordinate, while PLM remains primarily a repository for product data. When collaboration is not integrated, knowledge becomes scattered across channels, making it harder to maintain traceability of decisions, to capture rationales at the moment they are produced, and to ensure that lessons learned are visible and reusable beyond a team or project. At the same time, 80% of participants agreed that PLM contributes to error reduction and increased transparency when implementation and training are adequate. This result indicates that practitioners recognize PLM’s potential benefits but also suggests that these benefits materialize only when PLM is treated as a socio-technical system supported by coherent configuration, disciplined workflows and user capability building. The contrast between the high perceived value of PLM (80%) and the reported gaps in collaboration integration (58%) reinforces the interpretation that the main issue lies not in the existence of technology, but in its level of operational integration and adoption.

Taken together, these results support the view that technology is a necessary enabler but not sufficient on its own, as access, reuse and collaboration challenges coexist and tend to reinforce one another.

Figure 4 summarizes the key survey outputs and provides quantitative support for the subsequent causal modelling step.

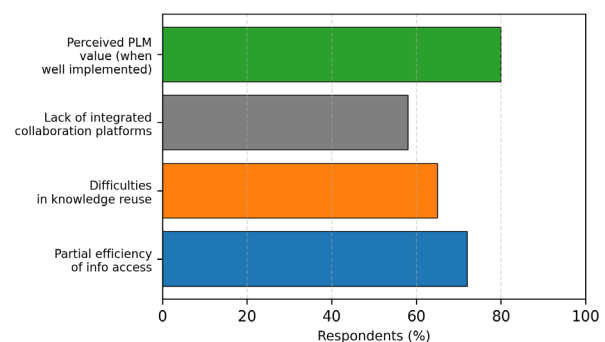


Fig. 4. Survey results on perceived efficiency of knowledge-management practices in industrial product design.

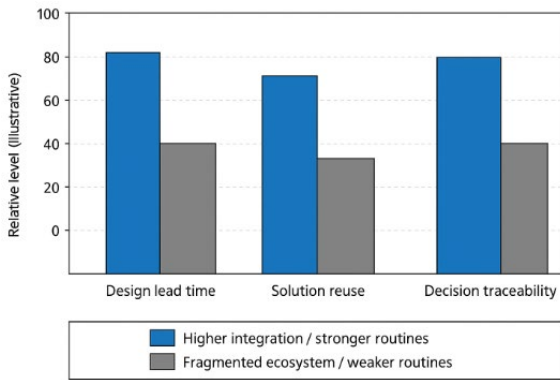


Fig. 5. Cross-case patterns on integration, reuse and traceability (illustrative salience).

4.3. Cross-case insights

Cross-case analysis reveals systematic differences between organizations characterized by higher levels of digital integration and those operating with fragmented tool landscapes and weaker knowledge-management routines. In cases where PLM–ERP–CAD connectivity, consistent configuration management, and standardized documentation templates were in place, organizations reported shorter design lead times, fewer rework loops, and smoother coordination across functions and sites. Conversely, cases marked by fragmented digital ecosystems and limited codification exhibited repeated problem-solving cycles and elevated coordination costs. Figure 5 presents an illustrative comparison of cross-case patterns (qualitative salience).

4.4. Ishikawa causal model and proposed solutions

The Ishikawa causal model (Fig. 6) consolidates the empirical evidence into six categories and clarifies how knowledge-management inefficiencies are generated through interdependent causes rather than isolated issues. In the People branch, the diagram highlights gaps in digital competencies, communication barriers and resistance to change, which hinder consistent adoption of shared knowledge routines. In practice, these factors reduce the quality and speed of knowledge transfer between disciplines, increase reliance on informal “know-who” networks, and make it difficult to standardize how critical knowledge is captured and reused. When teams lack a shared baseline of digital skills and communication practices, even well-designed tools and processes tend to be used inconsistently across functions and sites.

In the Methods branch, insufficiently standardized procedures for capturing and reusing knowledge (e.g., missing codification of expertise and weak “lessons learned” practices) reduce organizational learning and lead to repeated problem-solving. This branch emphasizes that the organization may have significant expertise yet still fail to transform it into reusable assets because routine mechanisms (templates, decision logs, milestone deliverables, validation feedback capture) are incomplete or not enforced. As a result, knowledge remains project-specific, design rationale is not systematically recorded, and teams frequently “rediscover” solutions under time pressure rather than reusing validated approaches.

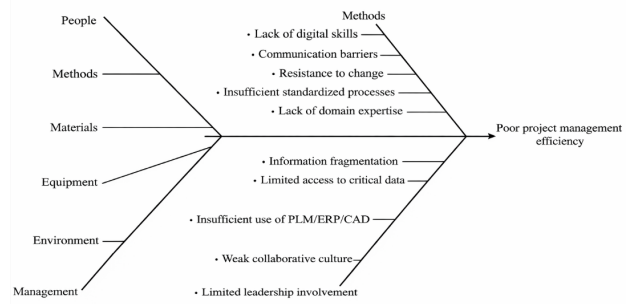


Fig. 6. Ishikawa diagram of root causes for knowledge management inefficiencies in complex industrial product design.

The Information (Materials) branch reflects fragmentation of information and limited access to critical data, which directly impacts traceability and decision quality. Fragmentation typically manifests through scattered repositories, multiple versions of documents, inconsistent naming conventions and unclear data ownership. Limited access to critical data further amplifies these effects by slowing down decision cycles and increasing the likelihood that teams work with partial or outdated information. Consequently, engineers spend additional time searching, reconciling and validating information instead of progressing toward stable design decisions.

The Equipment (IT) branch indicates underuse of PLM/ERP/CAD capabilities and inadequate integration, which weakens traceability and daily collaboration. Importantly, the model does not imply that technology is absent; rather, it suggests that digital systems are not configured or adopted to function as an integrated knowledge backbone. Weak interoperability between PLM, ERP and CAD and the absence of unified collaborative tooling can push teams toward parallel channels (emails, local folders, spreadsheets), reinforcing fragmentation and undermining the “single source of truth” principle. This branch therefore connects technical limitations with adoption behavior and highlights that system value depends on coherent configuration and disciplined usage.

The Environment branch points to a weak collaborative culture and challenges of geographically distributed work. Cultural elements such as limited incentives for sharing, low trust, uneven maturity across sites, and time pressure can discourage systematic documentation and reuse. In distributed settings, these factors become more critical because effective collaboration requires structured communication and stronger traceability; without them, misunderstandings propagate across functions and locations.

Finally, the Management branch emphasizes limited leadership involvement and unclear governance for knowledge assets. When governance is weak, roles and responsibilities for knowledge stewardship remain ambiguous, and knowledge capture becomes optional. In such conditions, even strong technical solutions fail to create sustainable change because teams are not aligned on what must be captured, when it must be captured, and how it should be validated and reused.

As summarized in Figure 6, these causes do not act independently; instead, they reinforce one another and amplify delays and rework loops in complex product design. For example, weak methods and unclear governance intensify fragmentation, while limited digital competencies and inadequate collaboration tools reduce the effectiveness of PLM and prevent consistent reuse of expertise. This interconnected structure supports the need for integrated interventions rather than isolated corrective actions.

Based on the causal structure in Figure 6, three integrated solution directions are prioritized. (1) Digital integration through unified collaborative platforms connected to PLM aims to reduce fragmentation and improve traceability by ensuring that key product information, decisions and issues are accessible and controlled in a coherent environment. (2) Standardized codification and “lessons learned” workflows embedded in project milestones ensure systematic capture and reuse by formalizing decision rationale, change justification and validation feedback as mandatory outputs at defined stages. (3) Culture and capability building through continuous training and leadership-driven incentives strengthens collaboration and sustains consistent knowledge-sharing behaviors, addressing the human and managerial conditions required for long-term adoption. Together, these directions reflect the core implication of Figure 6: improving knowledge management in complex industrial product design requires aligned action on technology, processes and organizational culture, because focusing on only one dimension tends to shift bottlenecks rather than remove them.

5. FURTHER RESEARCH

Future work can extend this exploratory foundation in four complementary directions, with the goal of increasing both the robustness of the evidence and the practical transferability of the proposed improvement model. First, larger multi-industry samples can be used to quantify relationships between KM practices, PLM maturity and measurable performance indicators such as lead time, rework rate and defect escape. Expanding the sample across different industrial sectors, product complexity levels and organizational maturity levels would allow comparative analysis and the identification of context-dependent patterns (e.g., which KM routines have the strongest impact under high product complexity, distributed development or intensive supplier involvement). In addition, future studies may employ structured maturity models for PLM/KM to enable benchmarking and to support statistical testing of associations between maturity levels and performance outcomes, including the identification of threshold effects (e.g., maturity levels beyond which improvements become significantly visible).

Second, AI and knowledge graphs can support automated capture of design rationale, semantic search and proactive recommendation of reusable solutions [5]. Future research can explore how generative assistants, natural language processing and graph-based representations can extract relationships between requirements, decisions, issues and validated solutions

from engineering documents, change requests and PLM records. Beyond retrieval, these approaches could provide contextual recommendations (e.g., suggesting similar historical cases, validated design patterns or “golden solutions” during early phases of product design) and could be evaluated through controlled pilots that compare decision time, rework frequency and user acceptance before and after AI/knowledge-graph integration. An additional direction is to study how trust in AI recommendations and data quality constraints influence adoption in engineering organizations.

Third, a dedicated KPI set for KM can be defined to monitor knowledge reuse, contribution rates and cross-team information latency. Beyond defining indicators, subsequent work should validate their operational feasibility, including how they can be reliably measured using existing digital traces (PLM logs, change management records, issue tracking systems). Future research may also investigate how KPI dashboards influence behavior over time—for example, whether making reuse visible increases documentation quality and reduces duplication, or whether it requires complementary incentives and governance mechanisms to avoid superficial “checkbox” compliance. A practical extension is to connect KM KPIs with project gates (design reviews, validation readiness) to test whether formal integration improves consistency and traceability of decisions.

Finally, the influence of organizational culture and leadership behaviors can be investigated with longitudinal designs to understand how learning routines become sustainable. Because KM adoption is shaped by incentives, trust and leadership commitment, longitudinal studies could track how training programs, role definitions (knowledge stewards), and governance policies affect collaboration quality and the stability of capture-and-reuse routines across multiple projects. This direction would help distinguish short-term improvements driven by tool deployment from long-term changes driven by cultural alignment, thereby clarifying which interventions create durable organizational learning in complex industrial product development. In addition, future studies could examine change-management mechanisms (communication cadence, leadership role-modeling, recognition systems) that best support sustained knowledge sharing in geographically distributed engineering teams.

6. CONCLUSIONS

This study confirms that knowledge management is a critical success factor for the design of complex industrial products in digitalized environments, where engineering performance depends on the ability to capture, structure and reuse expertise across multidisciplinary and often distributed teams. By combining evidence from expert interviews ($n = 12$) and a practitioner survey ($n = 48$), the research shows that dominant sources of inefficiency are systemic weaknesses in knowledge flow—information fragmentation, incomplete codification of tacit expertise and communication barriers. These issues translate into duplicated work, delayed decisions, repeated clarification

cycles and avoidable rework loops during the product development lifecycle.

The findings also highlight an important practical nuance: while PLM systems are widely recognized as enablers of transparency and error reduction, their impact is contingent upon disciplined process integration, user capability building and clear governance. In other words, technology alone does not ensure knowledge reuse; it must be supported by standardized routines, consistent adoption and leadership commitment. The proposed Ishikawa-based causal model consolidates the empirical evidence into a structured diagnostic framework that clarifies interdependence across People, Methods, Information, Equipment, Environment and Management. This synthesis supports a more actionable understanding of “where the bottlenecks really are” and why they persist across projects.

From an applied perspective, the study leads to an integrated improvement approach structured around three mutually reinforcing directions: (1) digital integration through PLM-linked collaborative platforms to reduce fragmentation and strengthen traceability; (2) standardized codification and embedded “lessons learned” routines at key project milestones to institutionalize reuse; and (3) culture and capability development, including continuous training and leadership-driven incentives, to sustain knowledge-sharing behaviors. Importantly, these directions should be implemented jointly, as isolated interventions tend to shift constraints rather than remove them.

Finally, the exploratory nature of the study and the sample scope limit statistical generalization; however, the convergence between qualitative and quantitative evidence strengthens analytical credibility and provides a solid foundation for broader, multi-industry validation. Overall, the research contributes a practical and transferable diagnostic logic for improving knowledge management in complex industrial product design and supports organizations seeking to reduce rework, increase consistency and accelerate innovation through systematic knowledge reuse. Ultimately, transforming dispersed experience into a traceable, reusable organizational asset – through aligned technology, standardized routines and leadership-supported culture – represents a decisive lever for reducing rework and

accelerating reliable innovation in complex industrial product design.

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