Commissioning as Workplace Learning: Visibility, Identity, and Tacit Knowledge Risks

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Abstract

Commissioning—the phase in which engineered systems transition from design to operation—creates a distinctive workplace learning ecology characterised by compressed timelines, high stakes, interdependent teams, and a heavy reliance on tacit knowledge. Despite its centrality to capability development, commissioning remains invisible mainly in organisational systems, standards and curricula. This structural invisibility shapes how participation, legitimacy and knowledge transfer unfold in practice, yet commissioning is almost absent from workplace learning research.

Drawing on sociotechnical safety theory, identity construction and practice-based learning, this paper introduces three constructs that explain learning vulnerability in commissioning environments: Commissioning Visibility Deficit (CVD), Identity Under Pressure Load (IUPL) and Tacit-Critical Knowledge Risk (TCKR). These constructs are integrated into the Commissioning Visibility–Risk Model (CVRM), which conceptualises commissioning as an interdependent learning ecology in which structural invisibility, legitimacy pressures, and tacit fragility shape capability continuity, participation, and inclusion. Two practice-informed vignettes illustrate how these dynamics manifest during high-risk commissioning episodes.

The paper extends workplace learning theory by showing how visibility, identity and tacit knowledge dependencies interact during complex technical work, and provides pathways for operationalising CVD, IUPL and TCKR in future empirical studies. The findings highlight the need to recognise commissioning as a critical site of workplace learning and organisational resilience.

1. Introduction

Commissioning engineering sits in a strange place in the project lifecycle: absolutely critical, yet barely theorised. It is the moment where design assumptions meet the real system, and the gap between the two becomes uncomfortably obvious. Latent faults, awkward interface behaviour, and odd dependencies that nobody noticed on paper tend to show themselves here (Odinaka et al., 2021; Infrastructure Australia, 2021). Unlike design or construction—both of which enjoy long-established methods and more precise boundaries—commissioning demands quick reasoning across disciplines, judgement under pressure, and a willingness to make decisions before everything is neatly lined up (van der Vorm et al., 2020; O'Connor et al.,2021; Whyte et al., 2016). Across infrastructure, energy, water, and nuclear projects, a surprisingly large share of early-life failures originates at this point, especially when integration and verification have been rushed or fragmented (Babar & Arain, 2019; O'Connor et al., 2021; Infrastructure Australia, 2021).

Yet commissioning is nearly invisible in the literature. Most research gravitates toward design or project management, and operations has its own extensive canon. Commissioning, meanwhile, is treated as a technical footnote rather than a socio-technical process in its own right (IAEA, 2018; WANO, 2024). This long-standing neglect creates what I refer to as a Commissioning Visibility Deficit (CVD): little institutional backing, shallow training infrastructure, and almost no shared conceptual language.

High CVD muddies expectations about competence, undermines capability development, and leaves organisations exposed at precisely the point when real-world complexity peaks (Collins, 2010; Jayaram & Bhatta, 2023).

At the same time, commissioning becomes a stage where engineers must navigate identity pressures. They work under observation, across boundaries, and often with incomplete information. It is an environment that naturally elevates Identity Under Pressure Load

(IUPL)—a mix of scrutiny, performance demands, gatekeeping, and thin psychological safety (Faulkner, 2009; Hatmaker, 2013; Ridgeway, 2011). Research across high-risk fields shows how these conditions constrain help-seeking, silence uncertainty, and push people away from the most complex tasks—effects that fall hardest on early-career and under-represented engineers (Powell et al., 2009; Billett, 2020).

The work also leans heavily on tacit knowledge. Much of what makes commissioning succeed—spotting anomalies, recognising early signs of system instability, knowing which tests matter more than others—sits outside documentation. When this expertise is concentrated in a few individuals, or disappears through turnover, organisations face heightened Tacit-Critical Knowledge Risk (TCKR) (Collins, 2010; Nonaka & Takeuchi, 1995). Numerous failures across water, energy, industrial, and nuclear systems point to this loss as a contributing factor.

From a workplace-learning perspective, commissioning creates a distinct learning environment (Beswick et al., 2025). Expertise develops in compressed, high-stakes conditions, often through informal mentoring or tacit transfer rather than structured programs (Sassanapitak et al., 2025). Work by Lave and Wenger (1991), Eraut (2004), and Fuller and Unwin (2003) makes clear that legitimacy, access to practice, and identity work are central to how engineers learn in such contexts. Commissioning illustrates these patterns vividly: participation is shaped by credibility, learning depends on tacit exchange, and invisibility narrows opportunities to develop capability. Situating commissioning within this scholarship extends current debates on involvement, knowledge flow, and learning in complex socio-technical systems (Billett, 2001).

Seen together, CVD, IUPL, and TCKR show commissioning not as a tidy technical phase but as a socio-technical learning ecology where visibility, identity, and knowledge stability shape organisational resilience. To trace these relationships, the paper introduces the Commissioning Visibility–Risk Model (CVRM), which links the three constructs into a single conceptual frame. The model illustrates how invisibility, identity strain, and tacit fragility interact with commissioning culture to influence safety, capability continuity, and inclusion. In doing so, the paper argues that commissioning warrants far greater scholarly and policy attention than it currently receives.

2. Methodology

This paper develops a conceptual theory through systematic construct specification and relational mapping. The aim is not empirical measurement, but the clarification and integration of constructs required to theorise commissioning as a socio-technical domain. This approach aligns with established pathways for theory-building in safety science, where conceptual specification precedes operationalisation and empirical testing (Wu & Wang, 2023; Liu et al., 2023; Bortey et al., 2022).

Commissioning exemplifies a phenomenon in which the absence of defined constructs, inconsistent terminology, and a fragmented knowledge base currently constrain empirical work. Conceptual development is therefore a necessary methodological step: it establishes the constructs, delineates their dimensions, and specifies their relationships in preparation for systematic validation.

The methodology proceeded in four stages. First, targeted synthesis of safety science, identity construction, and workplace learning literatures identified recurring patterns of invisibility, legitimacy pressures, and tacit vulnerability across commissioning environments. Foundational works on system safety and resilience (Dekker, 2014; Reason, 1997; Hopkins, 2019), identity construction in engineering (Hatmaker, 2013; Faulkner, 2009; Ridgeway, 2011), and knowledge in safety-critical domains (Collins, 2010; Nonaka & Takeuchi, 1995) were examined to locate commissioning within established theoretical traditions.

Second, three constructs were specified: Commissioning Visibility Deficit (CVD), Identity Under Pressure Load (IUPL), and Tacit-Critical Knowledge Risk (TCKR). Each construct was defined, its dimensions identified, and its boundary conditions clarified. Third, concept mapping positioned these constructs within a unified socio-technical learning ecology, identifying interaction pathways and feedback loops. Fourth, the constructs were integrated into the Commissioning Visibility–Risk Model (CVRM), which shows how structural invisibility, legitimacy challenges, and vulnerability converge to shape organisational risk.

To illustrate how these constructs manifest in practice, field-informed vignettes from the wastewater and nuclear sectors are included. These vignettes serve as theory-clarifying examples rather than empirical evidence, providing concrete anchors for the CVRM and demonstrating how invisibility, identity strain, and tacit fragility interact in real commissioning contexts. Section 7 outlines empirical pathways for operationalising and validating the CVRM in future research.

3. Theoretical Framework: Commissioning as a Socio-Technical Learning Ecology

This section introduces the theoretical foundations for reconceptualising commissioning as a socio-technical learning ecology. Drawing on safety science, identity construction theory and practice-based learning, the framework integrates three constructs—CVD, IUPL and TCKR—to explain how structural invisibility, identity strain and tacit-critical knowledge fragility interact within commissioning environments. Rather than treating these dimensions as separate organisational challenges, the framework positions them as interdependent features of commissioning practice that shape risk, capability and inclusion. The subsections that follow outline the theoretical traditions underpinning each construct and establish the foundations for the integrative model developed in Section 5.

3.1 Sociotechnical Systems Theory

Commissioning exemplifies the sociotechnical nature of risk, in which safety and performance emerge from interactions among human, organisational, and technical subsystems. Contemporary safety science emphasises that risk is never purely technical; it is produced through communication, coordination, and the distribution of expertise (Dekker, 2014). Commissioning amplifies these dynamics: troubleshooting occurs in real time, ownership of problems is often ambiguous, and consequences of failure are immediate.

This framing positions commissioning not as a marginal activity but as a critical node in sociotechnical systems. By highlighting the coupling of technical processes with organisational practices, commissioning becomes visible as a site where resilience depends on how expertise is shared, decisions are made, and learning is structured under pressure.

3.2 Status, Legitimacy and Identity Construction

Engineering is a status-coded profession in which legitimacy and credibility are negotiated through performance, visibility, and alignment with group norms (Ridgeway, 2011;

Hatmaker, 2013). Commissioning environments heighten these dynamics: engineers must demonstrate competence under observation, often with limited time and incomplete information. This pressure produces Identity Under Pressure Load (IUPL), a construct that captures how engineers' sense of expertise, status, and belonging shifts during commissioning episodes.

IUPL emerges from four dimensions: task demand, peer pressure, gatekeeping intensity, and psychological safety. When needs and scrutiny intensify while psychological safety is low, engineers face acute legitimacy strain. Research shows that such conditions suppress help-seeking, silence uncertainty, and constrain participation in high-risk technical settings (Faulkner, 2009; Hatmaker, 2013; Ridgeway, 2011).

Unlike broader identity research, IUPL addresses the distinctive pressures of commissioning work, where compressed timeframes and hierarchical norms amplify vulnerability. Engineers experiencing high IUPL are more likely to self-silence, withdraw from complex tasks, and exit field-based roles. By formalising IUPL, this paper provides a theoretically grounded construct for examining how legitimacy pressures shape workplace learning, participation, and retention in commissioning contexts.

3.3 Practice-Based Learning and Tacit Knowledge

Commissioning relies heavily on tacit, experience-based knowledge that is rarely documented in formal procedures (Salim, 2012). Troubleshooting, anomaly recognition, and system integration depend on cues acquired through shadowing, trial-and-error, and experiential judgment. When this expertise is concentrated in a few practitioners or lost through turnover, organisations face Tacit-Critical Knowledge Risk (TCKR)—a condition in which undocumented expertise has safety or operational consequences if absent (Collins, 2010; Nonaka & Takeuchi, 1995; Jayaram & Bhatta, 2023; Van Houton, 2023).

Workplace learning research highlights that much knowledge transfer occurs informally. Eraut (2004) emphasises that shadowing and unstructured practice are central to capability development, while Billett (2001) stresses that access to tasks and guidance determines whether tacit expertise is shared or withheld. Commissioning exemplifies these dynamics: high TCKR reflects restrictive learning environments where undocumented know-how is vulnerable, mentoring is inconsistent, and participation is constrained.

By formalising TCKR, this paper extends practice-based learning theory into commissioning contexts. It shows that tacit dependence is not only a safety issue but also a learning issue, where capability continuity depends on how organisations capture, diffuse, and legitimise experiential knowledge under high-stakes conditions.

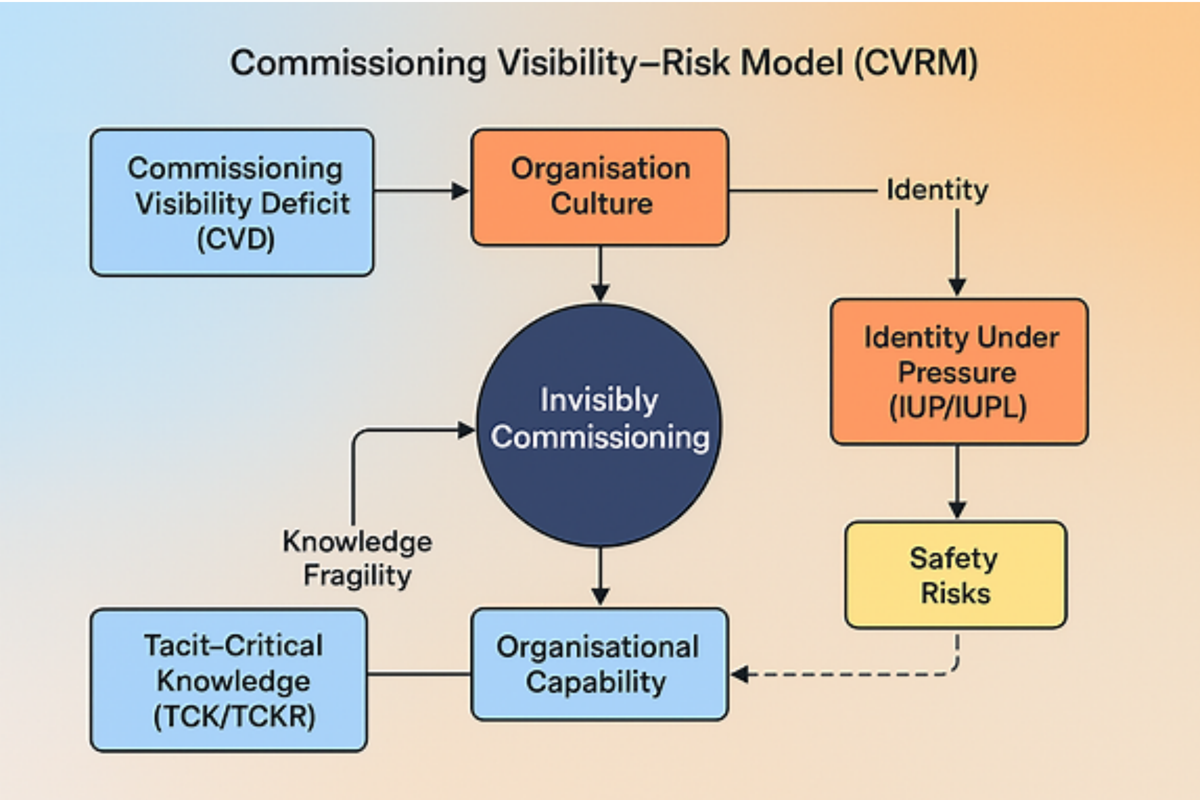

Figure 1. Commissioning Visibility–Risk Model (CVRM) A unified socio-technical framework showing how structural invisibility (CVD), identity strain (IUPL), and tacit-critical knowledge fragility (TCKR) interact with commissioning culture to shape organisational risk, capability continuity, and inclusion.

Figure 1 provides a schematic representation of the CVRM, IUPL and TCKR operate as interacting structural, cultural and knowledge-based conditions within commissioning environments. The diagram highlights the directional pathways through which structural invisibility (CVD) shapes commissioning culture, how that culture elevates IUPL and how both conditions amplify TCKR These interactions converge to influence three organisational outcomes—capability continuity, safety performance and inclusion—demonstrating that commissioning risk is an emergent property of the sociotechnical system rather than an isolated technical issue. The model makes explicit the relational logic developed throughout Sections 4–6 and provides a theoretical basis for the empirical propositions advanced in Section 7. Figure 1 therefore serves as the conceptual bridge between the construct definitions in Section 4 and the full CVRM elaboration in Section 6, highlighting the directional relationships that generate organisational risk.

3.4 Commissioning as workplace learning

Commissioning engineering can be reconceptualised not only as a sociotechnical risk domain but also as a distinctive site of workplace learning. The conditions of commissioning—compressed timelines, incomplete information, hierarchical scrutiny, and reliance on tacit expertise—create environments in which identity, knowledge transfer, and inclusion are continually negotiated (Okada, 2022).

From a community of practice perspective (Lave & Wenger, 1991), commissioning represents a boundary-crossing learning site. Engineers move between design, construction, and operations communities, negotiating legitimacy and competence in each (. This boundary work exposes novices to tacit practices and situated learning opportunities, but also risks exclusion when commissioning remains structurally invisible (high CVD).

Eraut (2004) highlights that much workplace learning occurs informally through shadowing, trial-and-error, and anomaly recognition. Commissioning exemplifies this: troubleshooting and system integration rely on undocumented cues and experiential judgment. Tacit-Critical Knowledge Risk (TCKR), therefore, maps directly onto workplace learning vulnerabilities, where the absence of structured capture mechanisms undermines capability continuity.

Fuller and Unwin's (2003) expansive/restrictive learning environments framework clarifies how commissioning culture shapes learning opportunities. High CVD produces restrictive conditions—limited mentoring, inconsistent access, and elevated identity pressures (IUPL). Conversely, recognition and resourcing create expansive environments where mentoring, structured transfer, and inclusive participation are possible.

Billett (2001) underscores that workplace learning depends on participatory practices. Commissioning culture determines who is permitted to engage in troubleshooting, how legitimacy is conferred, and whether tacit knowledge is shared or withheld. High IUPL constrains participation, reinforcing expertise bottlenecks, while low IUPL fosters collaborative learning and capability diffusion.

Together, these perspectives position commissioning as a workplace learning ecology in which invisibility, identity strain, and the fragility of tacit knowledge converge. Integrating CVD, IUPL, and TCKR into workplace learning theory strengthens the CVRM framework by showing that commissioning risk is not only a safety issue but also a learning issue: the sustainability of engineering capability depends on how organisation's structure, support, and legitimise learning during commissioning.

3.5 Contribution to Workplace Learning Theory

This manuscript extends workplace learning theory in three ways. First, it positions commissioning as a high-stakes learning ecology in which participation, identity and knowledge flow are shaped by structural invisibility—an environment rarely examined in existing workplace learning research. Second, it specifies how legitimacy pressures during commissioning influence help-seeking, participation and access to complex tasks, thereby extending identity-focused learning scholarship into a new engineering domain. Third, it conceptualises Tacit-Critical Knowledge Risk (TCKR) as a learning vulnerability rather than solely an operational one, showing how reliance on undocumented expertise restricts development affordances and limits capability continuity. Together, these contributions broaden current understandings of participation, identity construction and knowledge transfer in complex sociotechnical workplaces.

4. Three constructs

4.1: Commissioning Visibility Deficit (CVD)

Commissioning Visibility Deficit (CVD) is a structural construct capturing the extent to which commissioning is under-represented across standards, scholarly literature, and curricula. When commissioning is absent from institutional frameworks, it receives less attention, fewer resources, and limited structured training. High CVD obscures competency requirements, weakens shared methodological language, and elevates organisational risk (IAEA, 2018; IEA Annexe 47, 2010; Infrastructure Australia, 2021).

CVD comprises three dimensions: standards presence, literature presence, and curricular representation. Weakness in any dimension amplifies invisibility, reducing institutional support and obscuring commissioning's role in capability continuity. For example, omission from ISO/IEC standards or engineering curricula limits recognition of commissioning expertise and constrains its integration into professional development pathways.

From a workplace-learning perspective, high CVD reduces expansive learning affordances by limiting visibility, mentoring and legitimate access to practice. This constrains engineers' opportunities to participate meaningfully and develop capability during commissioning.

By formalising CVD, this paper provides a basis for empirical operationalisation. It clarifies how structural invisibility functions as a modifier in commissioning environments and establishes the foundation for the integrative CVRM framework.

Section 4.2: Identity Under Pressure Load (IUPL)

Identity Under Pressure Load (IUPL) captures the legitimacy work engineers perform during commissioning, where competence and belonging are negotiated under compressed timeframes and continuous scrutiny. IUPL emerges from four dimensions: task demand, peer pressure, gatekeeping intensity, and psychological safety.

High IUPL reflects conditions in which engineers must demonstrate competence with limited time and incomplete information. Research shows that scrutiny and low psychological safety suppress help-seeking and silence uncertainty (Hatmaker, 2013; Faulkner, 2009; Ridgeway, 2011). Unlike broader identity studies, IUPL addresses the distinctive pressures of commissioning work, where hierarchical norms and performance demands constrain participation.

In workplace-learning terms, high IUPL suppresses help-seeking, constrains participation and restricts access to complex tasks: legitimacy pressures therefore shape who is permitted to learn and the extent of their involvement in commissioning activities.

Engineers experiencing high IUPL are more vulnerable to self-silencing, withdrawal from complex tasks, and attrition—particularly in field-based roles. By formalising IUPL, this paper provides a theoretically grounded construct for examining how legitimacy pressures shape workplace learning, participation, and retention in commissioning contexts.

4.3: Tacit-Critical Knowledge Risk (TCKR)

TCKR denotes the vulnerability that arises when safety-, performance-, or operation-critical aspects of commissioning depend on undocumented, experience-based expertise held by a limited number of practitioners (Van Houton, 2023). As illustrated in Figure 1, TCKR emerges from the multiplicative interaction of three components: tacit intensity (T), knowledge holder vulnerability (V), and system criticality (S).

In commissioning environments—where troubleshooting, anomaly interpretation, and system-state verification rely heavily on experiential judgment—high TCKR reflects conditions in which tacit intensity is elevated, knowledge holders are organizationally fragile (e.g., turnover, retirement, contractor dependence), and the affected systems are highly safety- or operationally critical. The multiplicative relationship means that high values in any dimension amplify overall risk: even moderate tacit intensity becomes dangerous when knowledge holders are vulnerable and systems are critical.

This formulation clarifies how the concentration and instability of tacit expertise generate systemic fragility in commissioning contexts. High-TCKR environments—common in wastewater treatment, industrial automation, utilities, and energy infrastructure—exhibit persistent patterns of system fragility when tacit expertise remains undocumented or is held by a limited number of individuals.

Incident investigations consistently demonstrate that organisations dependent on vulnerable knowledge holders are prone to repeated commissioning failures, protracted troubleshooting cycles, and reduced capacity to anticipate anomalous conditions. Knowledge-management research further shows that the absence of structured capture mechanisms accelerates capability loss during turnover and inhibits the diffusion of critical insight across teams (Collins, 2010; Nonaka & Takeuchi, 1995; Jayaram & Bhatta, 2023).

TCKR therefore serves as a theoretically grounded construct for explaining how tacit dependence becomes an organisational liability within commissioning environments. Section 7.1 outlines the empirical pathways for operationalising, validating, and incorporating TCKR into systematic commissioning research.

To further clarify the boundaries between the three constructs, Table 1 provides a comparative overview of CVD, IUPL, and TCKR. The table highlights their core definitions, key dimensions, distinctive features, and example contexts. This synthesis makes explicit how the constructs differ conceptually and shows their complementary roles within commissioning environments.

Table 1 Comparative overview of CVD, IUPL, and TCKR

Construct	Core Definition	Key Dimensions	Distinctive Feature	Example Context
Commissioning Visibility Deficit (CVD)	Structural invisibility of commissioning in standards, research, and curricula	Standards presence, literature presence, curricular representation	Absence in institutional frameworks	Commissioning omitted from ISO/IEC standards
Identity Under Pressure Load (IUPL)	Identity strain under scrutiny in high-stakes commissioning	Task demand, peer pressure, gatekeeping, psychological safety	Focus on legitimacy and belonging	Junior engineers silenced in nuclear commissioning
Tacit-Critical Knowledge Risk (TCKR)	Vulnerability when safety-critical commissioning depends on undocumented expertise	Tacit intensity, knowledge holder vulnerability, system criticality	Reliance on undocumented know-how	Retiring wastewater manager holding undocumented emergency knowledge

As shown, each construct captures a distinct but interrelated dimension of commissioning risk: structural invisibility (CVD), identity strain (IUPL), and tacit knowledge fragility (TCKR). Together, they form the foundation for the integrative CVRM framework developed in Section.

Within workplace-learning theory, high TCKR reflects a restrictive learning environment in which undocumented expertise limits novices' opportunities to engage in shadowing, anomaly recognition, and experiential judgement, making capability development fragile and inconsistent.

From a community of practice perspective (Lave & Wenger, 1991), commissioning represents a boundary-crossing site where engineers move between design, construction, and operations communities. This boundary work exposes novices to tacit practices and situated learning opportunities, but also risks exclusion when commissioning remains structurally invisible (high CVD).

Commissioning culture shapes learning opportunities through the interaction of CVD, IUPL, and TCKR. High CVD produces restrictive conditions—limited mentoring, inconsistent access, and elevated identity pressures. Conversely, recognition and resourcing create expansive environments where mentoring, structured transfer, and inclusive participation are possible (Fuller & Unwin, 2003).

Eraut (2004) emphasises that much workplace learning occurs informally through shadowing, trial-and-error, and anomaly recognition. Commissioning exemplifies this: troubleshooting and system integration rely on undocumented cues and experiential judgment. Tacit Critical Knowledge Risk (TCKR) therefore maps directly onto workplace learning vulnerabilities, where the absence of structured capture mechanisms undermines capability continuity.

Table 2. Summary of Key Constructs in Commissioning Engineering.

Construct	**Definition**	**Drivers**	**Implications**
Commissioning Visibility Deficit (CVD)	Degree to which commissioning is absent from standards, research, and curricula	Liminal lifecycle position; lack of disciplinary ownership; time pressu re	Weak institutional support, under-resourced training, elevated organisational risk
Identity Under Pressure (IUPL)	Acute identity negotiation under scrutiny in high-stakes commission ing	Task demand and complexity; peer pressure; gatekeeping; low psychol ogical safety	Attrition, self-silencing, reduced participation, inclusion challenges
Tacit-Critical Knowledge (TCKR)	Tacit knowledge with safety/ operational consequences if absent	High tacit intensity; vulnerable knowledgeholders; safety-critical systems	Knowledge fragility, repeated failures, reliance key individuals, capability erosion

5. The Commissioning Visibility–Risk Model (CVRM)

The Commissioning Visibility–Risk Model (CVRM) integrates the three constructs—CVD, IUPL, and TCKR—into a unifying framework that reconceptualises commissioning as a socio-technical learning ecology. The model demonstrates how structural invisibility, identity strain, and tacit fragility interact to shape organisational resilience, capability continuity, and inclusion.

As shown in Figure 1, the CVRM positions CVD, IUPL, and TCKR as interdependent modifiers of commissioning culture. High CVD constrains recognition and resourcing, producing restrictive learning environments. Elevated IUPL reflects legitimacy pressures that suppress participation and knowledge flow. High TCKR signals vulnerability when undocumented expertise is both indispensable and fragile. Together, these conditions amplify organisational risk by limiting the diffusion of capabilities and weakening safety margins.

The CVRM also identifies pathways to resilience. Expansive learning environments, characterised by recognition, mentoring, and structured transfer, reduce IUPL and mitigate TCKR: policy recognition and curricular integration lower CVD, embedding commissioning expertise into professional development. By framing commissioning risk as both technical and learning-based, the CVRM provides a conceptual foundation for empirical research, structured training, and organisational policy.

The CVRM reframes commissioning risk as both a learning challenge and a technical one. By integrating visibility, identity pressure and tacit fragility, the model shows how learning participation and capability continuity are shaped by sociotechnical conditions. In doing so, it positions commissioning as a workplace learning ecology that requires deliberate design, resourcing, and institutional recognition.

5.1 Core Components

Compressed timelines, incomplete information, hierarchical decision chains and direct exposure to system risk characterise commissioning environments. This culture shapes access to learning opportunities, determines who is permitted to engage in troubleshooting, and sets expectations for behaviour under pressure. Commissioning culture is the base condition that structures identity dynamics and knowledge flows. Research in organisational and safety science shows that such high-pressure environments influence behaviour, communication and learning practices (Dekker, 2014; Edmondson & Lei, 2014).

The CVRM framework is built on three interdependent constructs—Commissioning Visibility Deficit (CVD), Identity Under Pressure Load (IUPL), and Tacit-Critical Knowledge Risk (TCKR)—each of which modifies commissioning culture in distinctive ways. Together, they form the core components of commissioning risk as both a technical and workplace learning issue.

CVD reflects structural invisibility. When commissioning is absent from standards, literature, and curricula, it receives less recognition and resourcing, producing restrictive learning environments.

IUPL captures legitimacy pressures. Under compressed timeframes and hierarchical scrutiny, engineers must continuously demonstrate competence, often suppressing help-seeking and participation.

TCKR highlights tacit fragility. When undocumented expertise is indispensable yet vulnerable, organisations face capability bottlenecks and safety risks.

As summarised in Table 1, these constructs interact to amplify organisational risk when invisibility, identity strain, and tacit dependence converge. Table 2 provides concise definitions, drivers, and implications, offering a foundation for empirical operationalisation.

By specifying these core components, the CVRM clarifies how commissioning risk is not only technical but also cultural and educational. This framing positions commissioning as a workplace learning ecology where resilience depends on recognition, legitimacy, and knowledge continuity.

5.2 Interaction Pathways

The CVRM identifies several pathways through which these components interact:

Pathway A: CVD → Culture & Resourcing

High CVD reduces the likelihood that commissioning will receive formalised processes, clear documentation, or structured learning pathways. This weakens commissioning culture, making it dependent on individual personalities and informal knowledge networks.

Pathway B: Culture → IUPL

Cultures with intense scrutiny, unclear expectations or strong hierarchical norms elevate Identity Under Pressure Load. Engineers in such contexts experience heightened legitimacy challenges and limited psychological safety.

Pathway C: Culture & CVD → TCKR

CVD increases reliance on tacit knowledge because commissioning is less likely to be documented or taught. Cultures with weak onboarding or inconsistent mentorship further heighten TCKR's vulnerability.

Pathway D: IUPL → Knowledge Access & Participation

High IUPL often constrains engineers' willingness to ask questions, volunteer for tasks or participate in troubleshooting. This reduces TCKR diffusion and reinforces expertise bottlenecks.

Pathway E: TCKR → Organisational Risk

High TCKR is associated with structural fragility: failures repeat, troubleshooting relies on key individuals, and system knowledge erodes quickly during turnover. Knowledge management and safety science research both emphasise the risks associated with undocumented expertise and single-point knowledge dependencies (Collins, 2010; Reason, 1997).

5.3 Outcomes

(1) Capability Continuity

Sustainable engineering capability depends on low TCKR, low IUPL and low CVD. When these conditions are not met, organisations repeatedly lose commissioning expertise and face long-term capability decline.

(2) Safety and Operational Performance

Elevated TCKR and IUPL are associated with increased safety risk, communication breakdowns, near misses and system instability. Sociotechnical and organisational research consistently demonstrates that identity dynamics, team climate and knowledge fragility significantly shape incident likelihood (Dekker, 2014; Edmondson & Lei, 2014).

(3) Inclusion and Retention

High IUPL disproportionately affects early-career and under-represented engineers, increasing attrition from commissioning roles. This feeds back into CVD: fewer practitioners with commissioning expertise means fewer opportunities for research, documentation and institutional recognition.

The interaction of CVD, IUPL, and TCKR within commissioning environments produces outcomes that extend beyond individual projects. At the organisational level, these dynamics shape capability continuity, safety performance, and inclusion. When commissioning remains structurally invisible (CVD), organisations risk under-investing in standards, curricula, and research, thereby perpetuating gaps in institutional knowledge. When identity strain is high (IUPL), engineers may disengage, conceal uncertainty, or exit commissioning roles altogether, weakening team resilience. When tacit knowledge is concentrated in vulnerable holders (TCKR), organisations face fragility in knowledge transfer, particularly during turnover or crisis events.

These outcomes are not isolated; they compound one another. For example, invisibility of commissioning in standards (CVD) can exacerbate identity strain (IUPL) by delegitimising commissioning expertise, while simultaneously heightening tacit risk (TCKR) by failing to formalise knowledge pathways. The CVRM therefore highlights commissioning as a socio-technical learning ecology where invisibility, identity pressure, and tacit dependence interact to shape organisational risk.

5.4 Integrative Logic of the Model

The CVRM demonstrates that commissioning risk is not just technical; it is structural, cultural, identity-based and knowledge-dependent. The model moves beyond traditional engineering analyses by showing that: CVD shapes the context; IUPL shapes participation; TCKR shapes capability; Culture shapes learning and risk.

Together, these dimensions shape safety, inclusion and continuity. By formalising these relationships, the CVRM positions commissioning as a domain that requires explicit research, training, investment, and policy attention — not an informal afterthought.

The constructs introduced above converge in the CVRM. This framework positions commissioning as a socio-technical learning ecology, showing how invisibility, identity strain, and fragility of tacit knowledge interact with culture to shape organisational risk, capability continuity, and inclusion.

CVRM extends existing sociotechnical frameworks by adding visibility deficit, identity strain, and tacit knowledge fragility as explicit constructs. While STAMP analyses hierarchical control structures (Leveson, 2011), AcciMap traces multi-level causal chains (Rasmussen, 1997), FRAM examines functional variability (Hollnagel, 2012), and resilience engineering emphasises adaptive capacity (Hollnagel et al., 2006), these frameworks presume visibility of work activities and stability of expertise. They do not capture how structural CVD, IUPL and TCKR systematically undermine safety and capability. CVRM addresses this gap by positioning commissioning as a distinct sociotechnical learning ecology where these three dimensions converge.

6. Illustrative Cases: Learning Breakdowns in Commissioning

The following cases illustrate how CVD, IUPL, and TCKR manifest in practice and demonstrate the learning breakdowns that occur when commissioning remains invisible in organisational systems.

The vignettes below are case-anchored illustrations that clarify the interactions among constructs in the Commissioning Visibility–Risk Model (CVRM). They are derived from publicly documented regulator incident reports and industry case material and are interpreted here as theory-clarifying examples rather than primary empirical reconstructions.

6.1 Wastewater Treatment Facility

This vignette draws on a documented sewage overflow incident reported by the Northern Territory Environment Protection Authority (NT EPA 2019). In this wastewater, the infrastructure experienced a loss of containment following a power outage. The incident report identified failures in the alarm and notification systems during the outage and restoration periods, contributing to delayed responses and uncontrolled overflows. The case is used here as a theory-clarifying illustration rather than a forensic reconstruction.

During a routine power interruption affecting wastewater pumping and treatment assets, influent pumping capacity was lost. Although backup systems and alarms were nominally in place, notification of the failure did not occur as expected. Alarm functionality during the outage and restart sequence was compromised, delaying operator awareness of rising levels within the system. By the time the loss of containment was detected, sewage overflow had already occurred, resulting in environmental discharge and regulatory intervention.

The post-incident review identified that, while individual components met design and maintenance requirements, critical interdependencies between the power supply, alarms, and system recovery behaviour had not been adequately verified under realistic disturbance conditions. Commissioning activities had focused on equipment sign-off and normal operating states, rather than whole-system behaviour during loss-of-power and restart scenarios. Knowledge of alarm behaviour, override states, and historical maintenance limitations resided with a small number of experienced personnel and was not formally documented or stress-tested during commissioning.

Interpreted through the Commissioning Visibility–Risk Model (CVRM), this incident illustrates how Commissioning Visibility Deficit (CVD) manifests when commissioning is treated as functional completion rather than as whole-system verification under credible failure modes. Identity Under Pressure Load (IUPL) is evident in the outage and restoration context, where time pressure, role ambiguity, and hierarchical escalation pathways constrained questioning and challenge. Tacit-Critical Knowledge Risk (TCKR) is exposed where an effective response depended on an undocumented understanding of alarm behaviour, power-system interactions, and recovery sequencing held by a limited number of individuals.

Together, these dynamics show how a technically compliant wastewater system can fail under its first real disturbance when commissioning learning, system visibility, and tacit knowledge transfer are structurally under-resourced. From a workplace-learning perspective, the incident reflects restricted participation, limited access to critical system knowledge, and the absence of structured learning opportunities during commissioning—conditions that directly amplify operational and environmental risk.

6.2 **Nuclear** Power Plant (NPP)

Analysis of 311 incident reports from Chinese NPP commissioning in the 2010s revealed widespread human error stemming from communication breakdowns and cognitive strain. Teams misinterpreted procedures, lost information during handovers, and failed to verify assumptions about system states.

High CVD was evident: procedures were formalised but blind to commissioning's cognitive complexity, treating "work as imagined" rather than "work as done." Extreme regulatory scrutiny created high IUPL, making junior staff reluctant to question instructions or admit uncertainty. High TCKR developed as tacit expertise in anomaly interpretation resided with senior SMEs and was lost through turnover.

The interaction pattern proved critical: CVD heightened reliance on tacit knowledge, while IUPL prevented personnel from surfacing gaps in understanding, thereby amplifying reliance on undocumented expertise. The result was preventable errors driven by systemic invisibility rather than individual incompetence (Zhang et al., 2020)

Interpreted through workplace learning theory, this case shows that procedural visibility does not guarantee learning visibility. High IUPL suppressed questioning and help-seeking, while high TCKR concentrated anomaly-recognition knowledge in senior experts. High CVD left commissioning learning structurally unsupported. These dynamics combined to restrict participation and limit the development of capabilities in a high-risk environment.

Within CVRM, the pattern is the same: CVD leaves commissioning cognitive work under-specified, IUPL suppresses questioning under scrutiny, and TCKR concentrates anomaly-interpretation skill in a small SME subset—creating predictable handover and verification failure modes.

7. Research Agenda and Empirical Operationalisation

7.1 Operationalising the Constructs

The constructs introduced in this paper—CVD, IUPL, and TCKR—require empirical operationalisation and validation. Developing psychometric instruments to measure these constructs across commissioning environments would enable systematic testing of the relationships proposed in the CVRM.

CVD measurement could proceed through curriculum audits, content analysis of accreditation standards, bibliometric mapping of commissioning research, and organisational policy reviews across water, energy, and industrial automation sectors. This would quantify the magnitude of visibility deficit across organisations, sectors and national contexts.

IUPL survey instruments would capture identity pressure, legitimacy strain, and psychological safety specific to commissioning contexts, with particular attention to variation across career stages and demographic groups. Longitudinal identity tracking and diary methods during start-ups would reveal how IUPL evolves across project phases.

TCKR operationalisation could employ expert elicitation, fault tree analysis, and network mapping of knowledge dependencies, enabling quantitative assessment of organisational vulnerability. Task shadowing, ethnography, and turnover vulnerability mapping would identify where tacit expertise creates single-point dependencies.

Longitudinal studies tracking how CVD, IUPL, and TCKR correlate with safety incidents, learning outcomes, and workforce retention would provide critical evidence for the model's predictive validity.

7.2 Research Propositions

The CVRM generates ten testable propositions for empirical validation:

Proposition 1 (CVD): Higher CVD is associated with weaker formalisation of commissioning tasks, lower documentation quality and reduced organisational learning maturity. Proposition 2 (IUPL): Higher IUPL is associated with reduced help-seeking, lower psychological safety and decreased willingness to participate in troubleshooting. Proposition 3 (IUPL-Equity): IUPL disproportionately affects early-career, contract-based and underrepresented engineers. Proposition 4 (TCKR): High TCKR is positively correlated with repeat commissioning failures, expertise bottlenecks and extended troubleshooting durations. Proposition 5 (TCKR-Intervention): Structured elicitation of tacit knowledge reduces TCKR by strengthening knowledge diffusion pathways. Proposition 6 (CVRM-Safety): Safety and operational performance decline as TCKR and IUPL increase, independent of technical system complexity. Proposition 7 (Culture-IUPL): Gatekeeping intensity mediates the relationship between commissioning culture and IUPL. Proposition 8 (Inclusion): Inclusion-focused commissioning interventions decrease IUPL and increase participation in complex troubleshooting. Proposition 9 (Learning): Teams using structured commissioning learning interventions demonstrate reduced TCKR and increased team learning rates. Proposition 10 (Regulation): Sectors with higher regulatory visibility of commissioning exhibit lower CVD, lower TCKR and stronger capability continuity.

7.3 Future Research Directions

Empirical validation of the CVRM requires diverse methodological approaches. Quantitative studies should develop and validate psychometric instruments for CVD, IUPL and TCKR, test propositions through surveys and longitudinal designs, and establish correlations with safety incidents and workforce outcomes. Qualitative research should employ ethnography of commissioning teams, interview studies with diverse practitioners, and case study comparisons across sectors and national contexts. Mixed-methods intervention studies could test commissioning learning designs, inclusion-focused interventions, and knowledge capture mechanisms.

Cross-sector and cross-national comparisons would investigate how regulatory structures influence CVD, how cultural norms shape IUPL, and how workforce models affect TCKR. Such work aligns with global calls for sociotechnical comparative research in engineering systems (Dekker, 2014; Hopkins, 2019).

Ultimately, establishing commissioning studies as a recognised scholarly field will require coordinated research programs, special journal issues, cross-institutional collaborations and ongoing construct refinement. This paper provides the theoretical foundation for such a field.

7.4 Limitations

This paper advances a conceptual framework rather than reporting primary empirical findings. The vignettes are used to clarify construct interactions and illustrate plausible pathways consistent with documented incident narratives; they are not presented as exhaustive causal reconstructions. The constructs (CVD, IUPL, TCKR) therefore require empirical operationalisation and validation across settings, using mixed methods (e.g., surveys, ethnography, incident analysis, and organisational audits). Sector coverage is also limited: wastewater and nuclear provide high-contrast examples of commissioning visibility and scrutiny, but the CVRM is expected to generalise most strongly to other high-reliability and tightly coupled domains (e.g., energy, utilities, industrial automation) rather than all engineering contexts. Finally, institutional, regulatory, and contracting differences across jurisdictions may moderate observed relationships, particularly the strength and expression of IUPL and the organisational distribution of tacit knowledge risk.

8. Implications

Commissioning engineering has long been treated as a marginal operational activity, yet the evidence presented here demonstrates that it is a socio-technical phase with unique vulnerabilities. The CVRM formalises these vulnerabilities through three constructs — CVD IUPL, and TCKR. This discussion synthesises the theoretical contributions, situates CVRM within broader debates in safety science and organisational theory, and reflects on implications for practice, policy, and equity.

8.1 Advancing Sociotechnical Safety Theory

Existing frameworks such as FRAM, STAMP, and AcciMap have been invaluable for analysing system variability, control failures, and multi-level causal chains (Hollnagel, 2012; Leveson, 2011; Rasmussen, 1997). However, they presume the visibility of functions, the stability of expertise, and the neutrality of participation. CVRM extends these perspectives by showing that commissioning is structurally invisible in standards and curricula, that identity pressures constrain participation, and that fragility in tacit knowledge creates single-point vulnerabilities. In this way, CVRM complements resilience engineering (Hollnagel et al., 2006) by specifying how invisibility and identity strain systematically undermine adaptive capacity. The model, therefore, advances sociotechnical safety theory by foregrounding commissioning as a distinct risk ecology. The interaction pathways identified in CVRM show how invisibility, identity strain, and tacit fragility converge to undermine organisational resilience. High CVD weakens culture and resourcing; high IUPL constrains participation; high TCKR erodes capability continuity. These dynamics explain why organisations with strong safety cultures still experience commissioning failures. Addressing them requires deliberate investment in documentation, mentoring, and psychological safety. CVRM thus reframes commissioning as a resilience challenge: not only about technical readiness but about sustaining capability across generations of engineers.

8.2 Commissioning as a Knowledge System

The discussion of TCKR highlights that commissioning is not merely a technical process but a knowledge system. When undocumented routines dominate, organisations face elevated TCKR, leading to repeated failures and capability erosion (Collins, 2010; Nonaka & Takeuchi, 1995). CVRM formalises this fragility, linking tacit dependence directly to safety and resilience outcomes. This reframing positions commissioning as a site where knowledge management and safety science intersect, requiring deliberate strategies for capture, diffusion, and validation. It also underscores the need for empirical research to operationalise TCKR and test its predictive power across sectors. Engineering knowledge is traditionally valued. A recurring theme across the vignettes is that commissioning failures often stem from structural invisibility: commissioning is absent from standards, accreditation, and curricula (IAEA, 2018; Infrastructure Australia, 2021). The CVD construct provides a measurable basis for quantifying this absence. Integrating commissioning into policy frameworks would reduce invisibility, allocate resources, and legitimise commissioning as a domain of expertise. This has implications for regulators, professional bodies, and educational institutions, which must recognise commissioning as more than a transitional activity. CVRM offers a theoretical foundation for such integration, making visible what has long been overlooked

8.3 Identity, Legitimacy, and Inclusion

Commissioning environments intensify identity work: engineers must perform credibility under scrutiny, negotiate legitimacy in hierarchical teams, and manage psychosocial load in compressed timeframes (Faulkner, 2009; Hatmaker, 2013; Ridgeway, 2011). The construct of

IUPL formalises these pressures, showing how high identity strain reduces help-seeking, constrains participation, and disproportionately affects early-career and underrepresented engineers (Powell et al., 2009). This has direct implications for inclusion and retention: when commissioning roles are perceived as hostile or exclusionary, organisations lose talent and reinforce invisibility. CVRM, therefore, contributes to equity debates in engineering by linking identity dynamics to safety and capability outcomes.

Commissioning does not become safer by being treated as invisible; it becomes riskier in quieter, more structural ways—through under-verified dependencies (CVD), suppressed uncertainty and constrained participation (IUPL), and fragile reliance on undocumented expertise (TCKR). The CVRM makes these failure mechanisms legible and therefore governable. For policy and practice, the implication is clear: commissioning must be explicitly recognised in standards and competency frameworks, resourced as a learning-critical phase (not a schedule afterthought), and supported through structured knowledge capture and psychologically safe escalation pathways. Doing so is not "nice to have"; it is how organisations protect capability continuity and avoid repeating preventable early-life failures in complex engineered systems.

9. Conclusion

This paper introduces the Commissioning Visibility–Risk Model (CVRM) as a framework for reconceptualising commissioning not only as a technical activity but also as a workplace learning ecology. By formalising CVD, IUPL, and TCKR, the model demonstrates how invisibility, legitimacy pressures, and tacit fragility interact to shape organisational resilience, capability continuity, and inclusion.

The CVRM extends existing sociotechnical approaches by adding visibility deficit, identity strain, and tacit dependence as explicit constructs. In doing so, it highlights commissioning as a domain where risk is simultaneously structural, cultural, and knowledge based. The illustrative vignettes show that these dynamics are not abstract but manifest in real commissioning contexts, producing outcomes that affect safety, retention, and long-term capability.

For workplace learning scholarship, CVRM positions commissioning as a boundary-crossing site where identity, knowledge transfer, and inclusion are negotiated under pressure. For practice and policy, it underscores the need to embed commissioning in standards, curricula, and organisational routines, ensuring that tacit expertise is captured, legitimacy pressures are mitigated, and visibility is enhanced.

By reframing commissioning risk as both technical and learning-based, the CVRM provides a foundation for empirical research, structured training, and organisational investment. It calls for commissioning to be recognised not as an informal afterthought but as a critical site of capability, safety, and inclusion in engineering practice.

Recognising commissioning as a site of workplace learning, rather than a marginal technical phase, opens new pathways to strengthen capability continuity, reduce identity strain, and improve tacit knowledge transfer in engineering organisations.

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