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Manufacturing Sovereignty

Adopting Additive Manufacturing in a High-Reliability Organization

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Abstract

As industrial facilities age beyond their design horizons, their supply chains shrink, leaving operators of critical infrastructure with component obsolescence, dependency on monopolistic suppliers, and unpredictable lead times. Additive manufacturing offers a route toward operational sovereignty, replacing physical inventory with on-demand digital production, yet its adoption in safety-critical environments remains poorly understood. This thesis investigates how a high-reliability organization can adopt additive manufacturing in maintaining technically complex, long-lived facilities. Drawing on the People, Process, and Technology framework and a sociotechnical perspective, it examines adoption across three dimensions: component selection, reverse engineering, and digital integration. The empirical basis is a qualitative case study of Vattenfall's nuclear division: eighteen semi-structured interviews at Forsmark and Ringhals, plus document analysis. Findings show that procurement operates reactively, generating maintenance debt and weakening Vattenfall's position toward suppliers. Reverse engineering relies heavily on tacit expert judgment at critical stages, resisting the near-automated narrative in the literature. Digital integration is blocked by an aggregation problem, diverging security frameworks between the nuclear sites and corporate IT, and an absence of organizational ownership. Together, these reveal that a secure digital warehouse is not a downstream task but a precondition for secondary adoption. In response, the study proposes a seven-gate flag system for component selection and an eight-stage reverse engineering workflow built around bounded codification: specifying the architecture while shielding the stages whose reliability depends on expert judgment. The central theoretical contribution is that organizational rigidity need not be overcome for adoption to proceed, but can be redirected.

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Populärvetenskaplig sammanfattning

Föreställ dig att en reservdel till ett kritiskt maskineri helt enkelt inte längre finns att köpa. Tillverkaren har lagt ned, lagret är tomt och den enda leverantören sätter priset helt på egen hand. För ägare av kärnkraftverk är detta en reell vardag. Mer än två tredjedelar av världens kommersiella kärnreaktorer är över trettio år gamla. Det skapar en krympande leverantörsbas och ett allt sårbarare beroende av externa aktörer för drift av samhällskritisk infrastruktur.

Additiv tillverkning, mer känt som 3D-printing, erbjuder en möjlig väg ur beroendet. Istället för fysiska reservdelar kan en organisation spara en digital fil och tillverka komponenten på plats när behovet uppstår. Men för en högförlitlig miljö som kärnkraft, där säkerhetskraven är extrema och förändring är hårt reglerad, är vägen dit inte enkel. Ingenjörskunnande lever i stor utsträckning hos erfarna specialister snarare än i manualer, vilket gör processen svår att automatisera.

Syftet med detta examensarbete är att undersöka de organisatoriska förutsättningar och hinder som formar introduktionen av 3D-printing i en organisation som inte har råd att göra fel. Studien genomfördes på Vattenfalls kärnkraftsdivision genom arton djupintervjuer med chefer och tekniska experter vid Forsmark och Ringhals.

Resultaten visar att dagens reaktiva reservdelsanskaffning skapar en underhållsskuld och försämrar Vattenfalls förhandlingsposition. Processen att 3D-skanna en sliten komponent och återskapa en digital modell är dessutom mer beroende av erfaret omdöme än vad litteraturen ofta antyder. Samtidigt existerar det digitala bibliotek som hela tillvägagångssättet förutsätter ännu inte. Det beror dels på att ansvaret inte tilldelats någon, dels på aggregationsproblematiken vilket betyder att en komplett samling komponentfiler i sig utgör en säkerhetsrisk eftersom den fungerar som en detaljerad karta över kraftverkets fysiska uppbyggnad.

Som svar på dessa fynd presenterar examensarbetet ett sju-stegs flaggsystem för att identifiera lämpliga komponenter samt ett strukturerat åtta-stegs arbetsflöde för omvänd ingenjörskonst. Det centrala bidraget är insikten att den organisatoriska tröghet som gör kärnkraft säkert inte behöver övervinnas för att ny teknik ska tas i bruk, utan i stället kan riktas om och användas som en drivkraft för förändring. Studien öppnar för framtida forskning om hur ramverken fungerar i praktiken och hur ett säkert digitalt komponentbibliotek bör utformas och förvaltas.

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1. When the Part no Longer Exists

Getting a spare part used to be straightforward. A component fails, a replacement is ordered, and operations resume. For a growing number of industrial organizations, that sequence no longer holds. Over the past decade, the conditions under which critical components are sourced have shifted in ways that challenge long-standing assumptions about availability, lead time, and price. The supply-chain literature has responded by extending the concept of resilience into the broader notion of viability. Ivanov and Dolgui (2020) define this as the capacity of a production network to survive prolonged structural uncertainty rather than transient shocks. What earlier research treated as predictable global procurement is now reconceptualized as one configuration among several, and a less reliable one in many sectors than long-standing operational practice presumes (Butollo et al., 2025).

One consequence of this reframing has been a renewed academic interest in sovereignty as a feature of industrial organization. Edler et al. (2023) define technological sovereignty as the capacity of a state, region, or organization to act autonomously over relevant technologies without one-sided structural dependency on external suppliers. In the energy sector specifically, this translates into values of self-sufficiency, resilience, and self-determination as the constitutive properties of a sovereign system (Timmermann and Noboa, 2022). For operators of critical national infrastructure, sovereignty is therefore not an aspirational political category but an operational requirement: the capacity to maintain function when the external supply that previously underwrote it can no longer be assumed.

The structural conditions under which this sovereignty problem is most acutely felt are concentrated in long-lived industrial facilities whose original equipment is no longer supported by the supply base that built it. The global nuclear fleet provides the most documented case. More than two thirds of the 442 commercial reactors currently in operation are over thirty years old (IAEA, 2020), and refurbishment for long-term operation has become the dominant operating strategy across OECD countries (OECD Nuclear Energy Agency, 2012). Long-term operation does not eliminate the obsolescence problem. It compounds it, since each additional decade of service pushes further original equipment manufacturers out of the market and forces operators into a shrinking, increasingly monopolistic supplier base (Karaani et al., 2025). Electric Power Research Institute (2008) estimated that approximately 20 percent of identifiable plant equipment in the nuclear sector is already obsolete in this technical sense, and the trend has not reversed. Where reactive sourcing predominates, the consequence is an accumulating backlog of deferred maintenance of the kind documented by Gholipour et al. (2025) for capital-intensive sectors more broadly.

One candidate response to this accumulating problem is additive manufacturing, a technology that builds physical components layer by layer directly from a digital file, commonly known as 3D printing. Rather than ordering a replacement part from a vendor that may no longer exist, an organization can store a digital model and produce the component on demand (Holmström et al., 2010). This shift from physical inventory to a digital archive reframes the spare parts question entirely. Empirical work with industrial practitioners has confirmed that the perceived benefits of digital spare parts include reduced lead times, lower inventory carrying costs, and protection against obsolescence-driven stockouts (Chekurov et al., 2018), and systematic review work has more recently positioned additive manufacturing as a supply-chain-resilience capability rather than a manufacturing technology in isolation (Naghshineh and Carvalho, 2022). It is precisely this capability that organizations such as Vattenfall, a state-owned Swedish nuclear operator managing aging facilities across two sites, are now beginning to explore as a route toward operational sovereignty.

The case examined in this study is Vattenfall, a state-owned Swedish energy company with approximately 21,000 employees and majority ownership of five nuclear reactors at Forsmark and Ringhals (Vattenfall, 2024a). In 2023, these facilities accounted for nearly 30 percent of Sweden's total electricity generation (Vattenfall, 2024b), and the company is currently assessing the extension of reactor operation from 60 to 80 years, deepening its long-term commitment to its installed base (World Nuclear News, 2024). This scale and ownership structure make Vattenfall a systemically important institution in the sense defined by the OECD (2012): an organization whose operational failure would pose risks to national financial and societal stability. Operating aging nuclear facilities under strict safety mandates, Vattenfall is precisely the kind of High-Reliability Organization that Weick and Sutcliffe (2007) describe as one that must achieve near error-free performance in environments where failure could be catastrophic. It is in this context that the organization is now beginning to explore additive manufacturing and reverse engineering as a route toward greater operational sovereignty over its supply chain.

This sovereignty argument has so far been framed in physical terms, as the capacity to produce a component when its external supplier can no longer be relied upon. Yet the shift from a physical warehouse to a digital one (Holmström et al., 2010) relocates the problem rather than removing it. Once a spare part exists as a digital model rather than as physical stock, the capacity to store, retrieve, and share that model securely becomes a precondition for the entire approach. For an organization classified as critical national infrastructure, this digital dimension is not a downstream technical detail but a governance question in its own right, since a library of design files comprehensive enough to be operationally useful is, by the same logic, a detailed map of the plant's physical configuration. The adoption of additive manufacturing in a high-reliability organization therefore depends as much on how digital assets are governed as on whether components can be printed.

Most research on additive manufacturing asks whether the technology works and how to implement it. Less attention has been paid to what happens when the organization adopting it is deliberately built to resist unvalidated change, and when the expertise the technology depends on cannot be fully written down and transferred to others. This study addresses that question through an in-depth qualitative case study of Vattenfall's nuclear division, examining how component selection, reverse engineering workflows, and digital integration can be configured within an organization where operational reliability is not merely a goal but a constitutional requirement. In doing so, it develops two practical design proposals grounded in empirical data and raises a broader question: whether the same organizational logic that makes a high-reliability organization safe might also, if redirected rather than bypassed, be what makes new technology adoption possible.

1.1 Purpose

The purpose of this study is to examine the organizational attitudes, barriers, and opportunities that shape the adoption of additive manufacturing in a high-reliability organization maintaining technically complex, long-lived industrial facilities.

1.2 Research Questions

These questions guide the development of practical frameworks for component selection and reverse engineering and examine the digital-integration conditions on which both depend, all within the organization's existing governance structure.

RQ1: What supply-chain conditions and organizational attitudes shape the identification and prioritization of components for additive manufacturing, and how can the selection process be configured to reflect them?

RQ2: What barriers and opportunities characterize the reverse-engineering workflow that converts physical components into validated digital models, and how can that workflow be structured given those constraints?

RQ3: How do organizational structures and IT security measures affect the digital integration required for additive manufacturing?

1.3 Delimitations

First, it addresses the organizational conditions for adopting additive manufacturing rather than the materials science and printing process itself. Questions of print parameters, material science, and the choice of a specific printing technology fall outside its scope. Second, the two design proposals developed in Chapter 5 are derived from interview and document data and are not tested through a full implementation cycle, their validation is identified as a direction for future research. Third, the digital-integration analysis (RQ3) is pursued at a diagnostic level: the study explains why a governed digital library does not yet exist and what conditions its design would have to satisfy, but it does not specify the technical architecture of such a system. The empirical focus is limited to Vattenfall's two Swedish nuclear sites, Forsmark and Ringhals, supplemented by a small number of external industry partners.

1.4 Key Concepts

Reverse Engineering

Reverse engineering is the process of transforming a physical component into a functional digital model that can be used in CAD-based manufacturing. Unlike straightforward replication, the goal is to reconstruct the original design intent of a component, capturing the geometric and structural properties that define how it performs under operational conditions (Hopkinson and Dickens, 2003). This challenge is compounded when the component being reconstructed is worn or damaged and original drawings are missing or incomplete, forcing the engineer to distinguish between operational degradation and the component's intended geometry. In practice, reverse engineering is a multi-stage workflow in which errors can accumulate at every step (Turek et al., 2024), and the transition from raw scan data to a validated solid model depends on both complex reconstruction algorithms and expert engineering judgment that resists full codification (Boryga and Kołodziej, 2022).

Additive manufacturing

Additive manufacturing (AM) is a production technology that builds physical components layer by layer directly from a digital file, commonly referred to as 3D printing. By mirroring the geometric specifications defined in a CAD model, the technology enables the fabrication of highly complex components that conventional subtractive methods cannot reliably reproduce (Abdulhameed et al., 2019). For organizations managing aging industrial facilities, the strategic significance of AM extends beyond its technical capabilities. Rather than maintaining a physical inventory of spare parts, an organization can instead store digital models and produce components on demand, effectively replacing a physical warehouse with a digital one (Holmström et al., 2010). Systematic review work has positioned AM as a supply-chain-resilience capability rather than a manufacturing technology in isolation, making it particularly relevant for organizations facing component obsolescence and shrinking supplier bases (Naghshineh and Carvalho, 2022).

Component obsolescence

Component obsolescence occurs when a part transitions from a state of availability to unavailability from its original manufacturer, typically because the supplier has exited the market, gone bankrupt, or discontinued the product line (Karaani et al., 2025). In long-lived industrial facilities such as nuclear power plants, this is a pervasive and compounding problem. The Electric Power Research Institute (2008) estimated that approximately 20 percent of identifiable plant equipment in the nuclear sector is already obsolete, and the problem deepens with each additional decade of operation as the original supplier base continues to shrink. Critically, obsolescence does not cause immediate failure. Because components continue to function until a replacement is required, the problem remains hidden until the organization is forced into a reactive sourcing mode under time pressure, often during narrow and costly maintenance windows (Karaani et al., 2025).

High-Reliability Organization

A High-Reliability Organization (HRO) is one that achieves near error-free performance while operating in environments where the consequences of failure could be catastrophic (Weick and Sutcliffe, 2007). Nuclear power operators are among the most studied examples of this organizational form, characterised by strict procedural governance, exhaustive pre-evaluation of any proposed change, and a deliberate reluctance to operate outside proven parameters. What outside observers often interpret as organizational resistance is more accurately understood as a functional strategy, where stability and predictability are actively maintained as prerequisites for safety (Pettersen and Schulman, 2019). For Vattenfall, this means that the adoption of any new technology, including AM, must demonstrate that it does not compromise the reliability the organization is built to protect.

Maintenance debt

Maintenance debt refers to the accumulating backlog of deferred upkeep that builds when necessary maintenance cannot be performed due to a lack of available components, time, or resources (Gholipour et al., 2025). The problem is compounded by the fact that organizations often lack full visibility over which components are at risk, as information about repairability becomes buried in legacy documentation or normalised through a workplace culture of *making do* with aging equipment (Ford, 2018). In capital-intensive sectors such as nuclear power, this hidden vulnerability is particularly costly, since narrow revision windows leave little room to resolve faults that were not identified in advance. Left unaddressed, maintenance debt drives organizations into increasing dependence on a shrinking and expensive external supplier base, directly undermining the operational sovereignty they rely on (Gholipour et al., 2025).

2. Organizational resistance to change: A Theoretical Framework

To understand the implementation of new manufacturing technologies within safety-critical environments, this study adopts a sociotechnical perspective. This tradition originates with Trist and Bamforth (1951), who established that organizational performance is determined by the "interrelation of a technical system and a social system." Rather than treating AM as a standalone technical innovation, the framework conceptualizes it as an intervention in a coupled system where technical requirements and social structures shape each other in ways that make isolated optimization of either dimension insufficient.

To operationalize this perspective, the study utilizes the People, Process, and Technology (PPT) model. The roots of this model are found in Leavitt's (1964) "Diamond Model" which emphasized that change in one organizational component inevitably impacts the others. Sjödin et al. (2018) confirm that successful implementation in manufacturing depends on a structured approach focused on these three interdependent dimensions to address the systemic nature of production changes. By organizing the framework around Process, Technology, and People, this study can analyze how innovation is integrated into the complex setting of a HRO, and how the three dimensions interact to either enable or obstruct the transition toward a digital supply chain.

The framework is developed in four steps. Section 2.1 addresses the *Process* dimension through the concept of mindful inertia, which explains how rigorous procedural governance functions as a reliability mechanism. Section 2.2 addresses the *Technology* dimension through component obsolescence, maintenance debt, and the logic of internalizing production via rapid manufacturing. Section 2.3 addresses the *People* dimension by distinguishing primary from secondary adoption and by examining why infusion into daily practice depends on the conversion of tacit expertise into codified process. Section 2.4 integrates these dimensions around three sociotechnical tensions that structure the subsequent analysis.

2.1 Process: Mindful Inertia in High-Reliability Organizations

Within the PPT model, the process dimension refers to the methods and workflows through which tasks are organized and managed. In the context of a HRO, these processes are defined by extreme requirements for stability and safety, where resistance to change is often a functional strategy rather than a dysfunctional one.

An HRO is defined as an organization that achieves nearly error-free performance while operating in environments where failure could be catastrophic (Christianson et al., 2011). Reliability is not a permanent state but a dynamic process in which safety is managed through a preoccupation with failure and a reluctance to simplify. In high-risk sectors like nuclear power, these principles ensure that safety is treated as a constant effort to prevent any potential accident (Christianson et al., 2011). Because such organizations are strictly prohibited from operating outside of proven analytical parameters, any modification necessitates a comprehensive and often lengthy system-wide evaluation (Pettersen and Schulman, 2019).

What outside observers frequently label as organizational resistance is more accurately conceptualized as *mindful inertia*: a deliberate strategy designed to prioritize systemic stability over rapid innovation (Pettersen and Schulman, 2019). This functional skepticism serves as a critical counterbalance to unanalyzed technological shifts, ensuring that safety remains the paramount objective even under extreme operational requirements. Such rigorous approval processes reflect an institutional commitment to maintaining current reliability levels, where managers purposefully avoid taking risks simply to reduce other risks. This structural demand for exhaustive analysis dictates that the introduction of any new technical element remains strictly governed by the continuous requirement to demonstrate that the organization's established reliability is not being compromised (Pettersen and Schulman, 2019).

The tightly coupled nature of HRO operations means that even minor changes to standardized routines can destabilize the complex dependencies that maintain safety. Because the high cost of failure prevents the use of trial and error, these organizations must rely on exhaustive analysis to ensure success before any implementation. Any technical transition must also remain effective across multiple organizational layers, including both routine tasks and high-pressure emergency situations. This inherent rigidity acts as an organizational immune system that protects the stable environment from the uncertainty and variance that innovation often brings (LaPorte and Consolini, 1991). Mindful inertia therefore sets the procedural baseline against which any adoption of new manufacturing technology must be evaluated.

2.2 Technology: Component Obsolescence, Maintenance Debt, and the Case for In-House Rapid Manufacturing

While the mindful inertia of HROs protects organizational processes, it often produces a parallel stagnation within the technology dimension of the PPT model. As external innovation cycles render internal hardware obsolete, the organization moves from a state of controlled stability to one of technical decay. The technology dimension therefore addresses not the novelty of AM in itself, but the structural conditions that make its adoption strategically relevant for HROs.

Ford (2018) argues that HROs are vulnerable to a specific form of drift in which aging and hard-to-replace components are mentally reclassified from safety concerns into routine procurement problems. When organizations treat obsolescence as an administrative matter rather than a reliability risk, they lose the analytical sensitivity needed to detect latent failure before it becomes a crisis. Ford further notes that information about a component's repairability is often buried in legacy documentation or hidden by a workplace culture that normalizes working with aging equipment, weakening the preoccupation with failure that defines reliability-seeking behavior (Ford, 2018).

This loss of sensitivity is closely linked to an over-reliance on reactive maintenance, where repairs are only performed after a component has already failed. While this approach is sometimes chosen for its minimal initial costs, it creates a significant *maintenance debt*: short-term savings result in much higher long-term expenditures and escalating repair costs, which in capital-intensive sectors can be devastating (Gholipour et al., 2025). Unlike proactive methods such as Condition-Based or Predictive Maintenance, which use real-time data to solve problems before they arise, a reactive stance creates a state of mindlessness that ignores or misses early warning signals. This shift toward emergency maintenance not only increases safety risks but also disrupts the production process, leaving the organization unable to optimize its resources or plan for future stability (Gholipour et al., 2025).

To break the cycle of escalating maintenance debt, Gholipour et al. (2025) propose a shift from merely managing failures to *Design-out Maintenance*, a specialized strategy that "seeks to eliminate the need for maintenance through improved design." In an HRO context, this transition is not merely a technical upgrade but a strategic move toward autonomy, ensuring that organizational resilience is not hindered by external supply chain failures. By adopting technologies that allow for on-demand, in-house manufacturing, the organization can in principle transform a reactive vulnerability into a proactive strength and neutralize the safety risks associated with technical obsolescence (Holmström et al., 2010).

What this strategic shift requires in practice is developed by Holmström et al. (2010), who analyze rapid manufacturing as a reconfiguration of the spare parts supply chain rather than a discrete technical capability. Crucially, Holmström et al. (2010) emphasize that the benefits of this capability are not captured by acquiring the equipment alone because they depend on new workflows for identifying candidate components, generating and validating digital designs, and integrating the printed outputs back into existing systems. The technology dimension of the PPT model therefore cannot be reduced to the printer itself. It encompasses the digital assets, validation procedures, and information flows through which a physical part becomes a printable file and a printable file becomes a qualified component. This embedded complexity is what links the technology dimension to the human capabilities addressed in the next section.

2.3 People: Primary Adoption, Secondary Adoption, and the Codification of Expertise

By adopting technologies that enable on-demand manufacturing, an HRO can in principle transform a reactive vulnerability into a proactive strength. However, this strategic move toward autonomy remains an empty mandate if the technology is not effectively integrated into the organization's daily operations. The people dimension of the PPT model therefore shifts the analytical focus from the firm's initial investment to the individual user's adoption of the tool, and further to the knowledge practices through which the tool is actually put to productive use.

The adoption of technology in an industry is a well-studied area. Traditional research often relies on the Diffusion of Innovation (DOI) theory by Rogers (2003) to explain these transitions. Rogers' model describes how an innovation is communicated through specific channels over time among the members of a social system. However, DOI is primarily based on voluntary adoption and often neglects the complex realities of implementing innovations within organizational settings where users may have no choice but to use a new technology following an authoritative decision.

Gallivan (2001) argues that this initial firm-level choice is best conceptualized as a *primary adoption* made by organizational leadership rather than by the workforce. Although this "go ahead" is a necessary precondition, it does not guarantee that the technology will be effectively integrated into daily work. A critical next step is therefore required within the organization. *Secondary adoption* is defined as the process through which individual users implement and adjust to the innovation in order to perform their jobs. This stage represents what Gallivan considers true organizational adoption, because it is where the technology is genuinely embedded in the work that the company performs. By focusing on secondary adoption, researchers move beyond the mere purchase of a tool and examine the assimilation process, how deeply a technology penetrates workplace routines, and the extent to which it transforms organizational culture and workflows (Gallivan, 2001). This study therefore treats primary adoption as its analytical point of departure, using Gallivan's framework diagnostically to examine what secondary adoption of a given manufacturing technology would require rather than to describe a completed process.

In Gallivan's (2001) framework, secondary adoption is not a single event but a sequence of post-adoption stages:

Adaptation: The innovation is developed or installed, and procedures are revised to fit the new system.

Acceptance: Employees are induced to commit to using the innovation in their daily tasks.

Routinization: The use of the technology becomes a normal, expected activity within the organization.

Infusion: The final and most meaningful stage, where the technology is used in a comprehensive manner to support higher-level work, leading to increased organizational effectiveness.

This "second wave" is essential because it is where the actual value of the technology is realized. Without successful secondary adoption and subsequent infusion, a primary adoption remains an empty mandate that fails to change how the organization operates (Gallivan, 2001).

In an HRO context, however, reaching infusion poses a distinctive challenge that Gallivan's framework implies but does not fully develop. Routinization and infusion presuppose that the work in question can be standardized into repeatable procedures. This presupposition is complicated by the nature of the knowledge that such work requires. Nonaka (1994) distinguishes between *explicit* knowledge, which can be articulated, documented, and transferred through formal language, and *tacit* knowledge, which is rooted in individual experience, skilled judgement, and situated practice, and which resists full articulation. Organizational learning, in Nonaka's (1994) account, proceeds through a continuous conversion between these two modes: tacit expertise must be externalized into explicit procedure for it to be shared, while explicit procedure must be internalized into practiced competence for it to be applied reliably in real situations.

This distinction has direct consequences for secondary adoption in safety-critical environments. Where a new technology depends on substantial tacit expertise, engineering judgement, interpretation of ambiguous physical signals, and craft-based discretion where routinization requires that this expertise be progressively externalized into auditable procedure without stripping out the discretion that makes the work effective (Nonaka, 1994). Where such externalization is incomplete, infusion stalls, not because the workforce rejects the technology, but because the work it supports cannot yet be reliably repeated by anyone other than the original expert. The people dimension of the PPT model is in this sense inseparable from the technology dimension: the digital assets and workflows described in Section 2.2 only become operational through the expert practices examined here.

2.4 Integrated Framework: Three Sociotechnical Tensions

The three dimensions developed above are not additive but interdependent, and it is in their interaction that the central analytical problems of this study emerge. Rather than summarizing each dimension in turn, this section identifies three sociotechnical tensions that arise at the intersections of Process, Technology, and People. These tensions form the analytical backbone of the subsequent discussion and map onto the study's research questions.

Tension 1: Stability versus Autonomy (Process versus Technology). The same organizational features that make HROs reliable, including mindful inertia, exhaustive qualification, and a reluctance to operate outside proven parameters, have also slowed the organization's response to external supply-chain failure (Pettersen and Schulman, 2019). This rigidity acts as an organizational immune system designed to handle risks introduced from outside, but it was not designed for dependencies accumulating from within (LaPorte and Consolini, 1991). As Original Equipment Manufacturers (OEM) exit the market and components become obsolete, the HRO's protective rigidity compounds into maintenance debt (Gholipour et al., 2025) and a growing dependency on a shrinking external supplier base (Ford, 2018). Design-out Maintenance offers a route out of this dependency through improved design (Gholipour et al., 2025), and rapid manufacturing provides the technical means to pursue it (Holmström et al., 2010), but pursuing it requires the organization to reconfigure the very procurement and qualification processes that mindful inertia is designed to protect. The analytical question raised by this tension is how component identification and prioritization can be reconfigured without compromising the reliability that the existing procedural regime secures (RQ1).

Tension 2: Automation versus Craft (Technology versus People). AM is frequently presented in the literature as a near-automated production method in which a digital file goes in and a physical part comes out with minimal human intervention (Abdulhameed et al., 2019), yet its deployment in an HRO setting depends on forms of expert judgment that are difficult to codify. Gallivan's (2001) stages of secondary adoption assume that innovation can be progressively routinized into normal organizational activity, but routinization is only possible to the extent that the underlying tacit expertise can be externalized into explicit, documentable procedure (Nonaka, 1994). Where that conversion remains incomplete, the workflow remains dependent on specific individuals and infusion is deferred. The analytical question raised by this tension is what technical and procedural bottlenecks characterize the workflow through which physical components are converted into validated digital artifacts, and how far these bottlenecks reflect the limits of codifiable knowledge rather than the limits of the technology itself (RQ2).

Tension 3: Security versus Scalability (Process versus People). The mindful inertia that governs physical operations extends by the same logic to the digital assets on which a digital supply chain depends. For an HRO classified as critical national infrastructure, design files, scan data, and inter-organizational exchanges must be governed by the same regime of exhaustive analysis and controlled access that applies to physical components (Pettersen and Schulman, 2019). This security posture is functionally necessary, but it pulls against the collaborative, low-friction digital integration on which the operational advantages of rapid manufacturing depend (Holmström et al., 2010). Secondary adoption can only reach infusion if the daily digital workflow is frictionless enough to become routine (Gallivan, 2001), if security protocols force users into manual or old-fashioned workarounds, the organization may achieve primary adoption while failing to progress beyond acceptance into routinization. The analytical question raised by this tension is how digital assets must be managed and secured so that the integrity demands of the HRO do not undermine the scalability that justifies the adoption in the first place (RQ3).

A further implication developed through the analysis of Tension 3 is that the HRO's organizational immune system is built to evaluate decisions within established units and is therefore not designed to govern risks that emerge at the boundary between units. As the empirical material reveals, the digital infrastructure question falls precisely in that gap.

3. Methodology

This chapter provides a description of the methodological choices made to fulfill the research purpose of exploring how workflows can be designed and implemented for the adoption of AM within a HRO.

3.1 Choosing Research Strategy

The research strategy is determined by the need to understand how technical innovation interacts with the high safety standards of the energy sector. A qualitative approach was selected to provide the depth required to explore this contemporary phenomenon within its real-life context (Yin, 2018). While a quantitative approach focuses on numerical patterns, this study requires an exploration of organizational processes and professional interpretations that cannot be captured through numbers alone. By focusing on Vattenfall's specific HRO context, the strategy enables an investigation into the nuances of nuclear safety culture and its impact on the transition to a digital supply chain.

3.1.1 Philosophical Assumptions and Research Strategy

The study adopts a constructionist ontology and an interpretivist epistemology (Bryman, 2016). The implementation of AM at Vattenfall is treated not as an objective external fact but as a social process shaped by organizational beliefs and collective practice, where "safety culture" and "workflows" are continuously co-created by personnel. This orientation motivates a qualitative strategy that prioritizes the subjective meanings attached to the transition toward a digital supply chain over numerical patterns, and it is well suited to capturing the descriptions of technical experts and managerial stakeholders in their real-life context (Yin, 2018).

The relationship between theory and data is abductive. Rather than testing existing theory or building it from scratch, the research moves iteratively between empirical material and the integrated framework of Chapter 2, which functions as a diagnostic lens while remaining open to unexpected findings (Dubois and Gadde, 2002). This iterative movement allows the framework to be refined as new insights emerge from the field while maintaining a strong link between empirical evidence and conceptual structure.

3.2 Research Design

To address the research questions concerning the implementation of AM within a HRO, a case study research design has been selected. A case study is defined by the detailed and intensive analysis of a single case, focusing on the complexity and unique nature of the setting in question (Bryman, 2016). This design is particularly suitable when the study seeks to understand why certain phenomena occur within their real-life context, especially when the boundaries between the phenomenon and context are not clear. By adopting this design, the research can capture the complex socio-technical interactions between technological innovation and organizational safety requirements that a broader, cross-sectional study might overlook (Bryman, 2016).

The choice of a case study design aligns with the qualitative nature of this research, as it allows for a holistic exploration of organizational processes and employee perceptions. According to

Yin (2018), case studies are empirical inquiries that investigate contemporary phenomena in depth, which is essential for this thesis as it examines the forming transition toward digital supply chains in the energy sector. This approach provides the necessary depth to identify specific procedural bottlenecks and cultural resistance, thereby ensuring that the findings are grounded in the specific operational reality of the organization. Consequently, this design facilitates a comprehensive understanding of the case before moving into the specificities of the selected organization.

3.2.1 Case Selection: Vattenfall

The case for this study is Vattenfall, a state-owned energy company that occupies a systemically important position within the Swedish energy sector. This background establishes Vattenfall as an exemplifying case, which is a case chosen because it provides a suitable context for research questions to be answered by capturing the circumstances of a commonplace situation in a specific field.

By focusing on Vattenfall’s nuclear division, the study analyzes an environment where the challenges of component obsolescence are met with the highest possible safety and regulatory standards. The organization’s strategic goal of supplying fossil-free electricity while maintaining sovereignty necessitates a transition from physical inventory to digital storage. Choosing an exemplifying case allowed the study to examine the typical challenges faced by HRO when adopting new manufacturing technologies, with implications that extend beyond AM to other technically complex innovations in safety-critical settings. This detailed focus on Vattenfall provides a robust foundation for the empirical data collection methods described in the following sections, starting with the preliminary literature review.

3.2.2 Semi-structured Interviews

The primary source of empirical data consists of semi-structured interviews conducted with managers and technical experts at Vattenfall. This method uses an interview guide with specified topics while allowing participants significant freedom to expand on their perspectives (Bryman, 2016). This balance between structure and flexibility is necessary to capture the lived experiences of employees involved in maintenance and procurement workflows. The sample included stakeholders selected through purposive sampling to cover diverse organizational roles, technical specialists in 3D scanning, maintenance managers, procurement officers, and regulatory experts. This variety helps the data reflect the full breadth of the organization's technical and social subsystems. Eighteen interviews were conducted in total. Three of these are not cited in the analysis, as their primary contribution was to provide contextual background and inform the researchers pre-understanding of the field, rather than to supply direct empirical evidence.

Data collection took place between February and April 2026. Interviews were conducted remotely via Microsoft Teams, in person at Vattenfall's sites at Forsmark and Ringhals, and through on-site visits to the company's office in Solna and to external partner organizations (Framatome, Amexci, and RISE). Sessions lasted between 45 minutes and, in the case of full-day site visits, several hours. Transcription was treated as a "first-round analysis exercise"

(Cope, 2020), forcing the researchers to engage closely with the nuances and professional interpretations of the respondents. This deep familiarity with the material is a prerequisite for the subsequent coding phase. By prioritizing the participants' own descriptions, the study stays rooted in the actual experiences of those managing the transition from physical inventory to digital supply chains.

Table 1: Interviews

Interview number	Respondent number	Area of expertise	Company	Online/In person	Site	Time	Date
Interview 1	Respondent 1 & Respondent 2	Obsolescence	Vattenfall	Online	Forsmark	60 min	17-Feb
Interview 2	Not referenced	Structural Engineer	Vattenfall	Online	Forsmark	60 min	18-Feb
Interview 3	Respondent 3	AM-expert	Vattenfall	In person	Solna	90 min	18-Feb
Interview 4	Not referenced	3D-print	Vattenfall	Online	Forsmark	60 min	23-Feb
Interview 5	Respondent 4	Design Engineer	Vattenfall	Online	Forsmark	55 min	6-Mar
Interview 6	Respondent 5	French nuclear engineer	Framatome	Online	Framatome	50 min	11-Mar
Interview 7	Respondent 6	Procurement	Vattenfall	Online	Forsmark	60 min	13-Mar
Interview 8	Not referenced	AM-printing	Amexci	In person	Amexci HQ	3,5 h	16-Mar
Interview 9	Respondent 7	Obsolescence	Vattenfall	Online	Ringhals	60 min	19-Mar
Interview 10	Respondent 8 & Respondent 9	Reverse engineering	Vattenfall	In person	Ringhals	90 min	19-Mar
Interview 11	Respondent 10	Maintenance Engineer	Vattenfall	In person	Ringhals	60 min	19-Mar
Interview 12	Respondent 11 & Respondent 12	Design Requirements & Structural Integrity	Vattenfall	In person	Ringhals	60 min	19-Mar
Interview 13	Respondent 13	Procurement	Vattenfall	In person	Ringhals	75 min	19-Mar
Interview 14	Respondent 14	Scanning Expert	RISE	In person	RISE Mölndal	6 h	20-Mar
Interview 15	Respondent 15 & Respondent 16	Quality Control	Vattenfall	Online	Ringhals	60 min	27-Mar
Interview 16	Respondent 17	Law	Vattenfall	Online	Forsmark	60 min	31-Mar
Interview 17	Respondent 18	Law	Vattenfall	Online	Ringhals	60 min	24 April
Interview 18	Respondent 19 & Respondent 20	IT-security	Vattenfall	In person	Ringhals	70 min	27-April

3.2.3 Narrative Literature Review

In the initial phase of the research, a narrative literature review was conducted in line with Ferrari's (2015) framework to establish the theoretical landscape and identify existing research gaps. Unlike a systematic review, which follows a rigid and transparent protocol often found in medical sciences, a narrative review allows the researcher to tell a story about the research area and engage critically with the ideas of other writers. This approach is particularly suitable for exploratory qualitative research, as it offers the flexibility to refine research questions as the review progresses and new concepts emerge from the reading (Ferrari, 2015). The review focused on the intersections of HRO, organizational resistance to change, and the technical requirements of AM.

The primary goal of this narrative review was to synthesize foundational research and practical insights from prominent figures across diverse fields, ensuring the study is anchored in a robust theoretical tradition. Given the emerging nature of this subject, the review extended beyond traditional academic literature to include cross-disciplinary implementations and expert commentary. This broad synthesis serves to justify the study's positioning and guides the reader toward the specific, novel contributions of this thesis. As noted by Bryman (2016), the narrative review is an interpretative tool that helps frame empirical findings within the broader academic discourse. This theoretical grounding was essential for developing interview guides and ensuring that data collection was targeted toward the most significant organizational challenges.

3.2.4 Document Analysis as a Complementary Source

Alongside the interviews, document analysis was used to corroborate and contextualize respondents' accounts. Internal Vattenfall material referenced during the interviews, including the KBM and TBM qualification provisions, the POMS obsolescence records, and legacy supplier contracts, was consulted to compare formal procedures with the descriptions provided by personnel. Rather than constituting a separately coded strand of findings, this material functioned as a check against the interview accounts and informed the design of the interview guides, helping to mitigate individual bias and ground the empirical picture in the organization's documented practice (Bryman, 2016).

3.2.5 Data Analysis Procedure

The collected empirical material was analyzed using thematic analysis, a structured approach to identifying and interpreting patterns within qualitative data. The analysis followed the iterative phases outlined by Braun and Clarke (2006), beginning with a thorough familiarization with the transcribed interviews. This was followed by the generation of initial codes, where segments of text were labeled to capture key ideas related to the research questions. This coding process is non-linear, requiring constant movement back and forth between the data and the emerging categories to capture the complexity of the organizational environment.

In the subsequent phase, the initial codes were grouped into broader themes organized around the three research questions. Material relating to component identification, procurement conditions, and organizational attitudes toward AM was grouped under RQ1. Material relating to the technical and procedural aspects of 3D scanning and reverse engineering was grouped under RQ2. Material relating to information security, digital infrastructure, and organizational ownership was grouped under RQ3. While the research questions provided the primary organizing structure, the exploratory nature of the study allowed for the emergence of themes that cut across these boundaries, particularly where attitudes and organizational culture shaped technical practices. This analytical procedure ensures that the final discussion is grounded in empirical evidence while maintaining the abductive link between observation and theory. The final themes were reviewed and refined to ensure they accurately represented the participants' perspectives on the adoption of AM.

3.3 Trustworthiness and Ethical Considerations

Because qualitative research depends on context and subjective interpretation, experts often use the term trustworthiness instead of the usual scientific benchmarks of validity and reliability. According to Bryman (2016), trustworthiness is established through four primary criteria: credibility, transferability, dependability, and confirmability. To ensure the credibility of this study, which concerns the internal logic and truth-value of the findings, credibility was supported by comparing interview accounts against internal Vattenfall documentation where available. This approach ensures that the interpretations are robust and reflect the complex social reality of the participants.

Transferability, as defined by Bryman (2016), refers to the degree to which findings can be applied to other settings. While this case study focuses specifically on Vattenfall's nuclear division, transferability is supported through the provision of thick description. By detailing the organizational context and safety-critical workflows, the researchers provide a descriptive database that allows other scholars to evaluate the applicability of the findings to similar HRO (Bryman, 2016). Furthermore, dependability relates to the consistency and transparency of the research process. To achieve this, all methodological choices, from the formulation of interview guides to the execution of thematic analysis, were documented to create a trustworthy audit trail (Bryman, 2016). This is complemented by confirmability, which ensures that the researchers maintained a reflexive stance, grounding all conclusions in empirical data rather than personal bias (Bryman, 2016).

Regarding ethical considerations, the study adhered to the principles outlined by Bryman (2016) and Diener and Crandall (1978), covering avoidance of harm, informed consent, protection of privacy, and absence of deception. All participants were fully informed of the study's purpose before data collection began, participation was voluntary, and the right to withdraw at any stage was explicitly communicated. All participants were anonymized to allow candid responses without risk of professional repercussion. Data was handled in compliance with the General Data Protection Regulation (GDPR) throughout the research process.

3.4 Methodological Discussion

The choice of a qualitative case study at Vattenfall allowed for deep insight into an HRO, but it also presents limitations. A single case study limits the statistical generalizability of the findings compared to a multiple-case design or a quantitative survey. However, given the unique regulatory environment of nuclear power, the depth provided by this design was prioritized over breadth. If a quantitative design had been chosen, the study might have identified broader trends in technology adoption but would have failed to capture the professional interpretations of safety culture that are central to the research questions. Furthermore, while the abductive approach provides flexibility, it requires a high degree of reflexivity to prevent the researchers' theoretical preconceptions from overshadowing the empirical data. To mitigate this, document analysis was used as a complementary check alongside the interviews, and the documentation of an audit trail was maintained to support the trustworthiness of the results.

4. Empirical Findings

As outlined in the Methodology in Section 3, the empirical findings are primarily based on eighteen semi-structured interviews conducted with technical experts and managers at Vattenfall and field experts from external partner organizations. Fifteen of these are directly cited. The findings are organized around three analytical areas that emerged from the interview material and correspond to the three research questions. Section 4.1 examines the factors that shape how components are identified and prioritized for AM, covering the supply-chain conditions, legal constraints, and organizational attitudes that determine whether a component becomes an AM candidate. Section 4.2 traces the technical and procedural steps through which a physical component is transformed into a validated digital model, from 3D scanning through reverse engineering to quality control (QC) handover. Section 4.3 examines the digital infrastructure and information security conditions that any future component library would have to operate within. Together, the three sections map the full path from identifying a candidate component to the point where a validated model should, in principle, be available for on-demand production.

4.1 Component Selection: Configuring Identification and Prioritization for Additive Manufacturing

This section aims to outline the factors that influence the identification and prioritization of components suitable for AM as a collaborative organizational process. A component has a specific lifetime that varies significantly depending on its size, function, and operational usage. When a component reaches the end of its life or fails, a replacement process is initiated to determine where and how a new part can be secured. Within Vattenfall’s nuclear operations, this workflow is typically triggered during revision periods when maintenance staff or technicians identify wear or failure. This need is then registered in the internal enterprise system by material planners based on established stock levels and reorder points. (Respondent 1 & Respondent 2, project leaders at Forsmark obsolescence team)

As a High-Reliability Organization, Vattenfall's decision-making is defined by a shift from a focus on sustainability toward a priority on resilience. In this context, risk minimization frequently outweighs direct manufacturing or procurement costs. Sovereignty has emerged as a critical parameter because Vattenfall is a systemically important institution for Sweden's societal and financial stability. Respondent 5, an expert at Framatome, a French nuclear component manufacturer, explains the growing vulnerability of traditional nuclear supply chains:

> In European countries, obtaining high-quality, large-scale casted components for nuclear applications is becoming increasingly difficult due to the dwindling number of local foundries capable of meeting these standards. To maintain European sovereignty over the component supply chain, we must develop alternative manufacturing routes. AM provides this alternative; while not applicable to every component, it serves as a solution for specific, dedicated use cases. (Respondent 5)

Framatome's position is that sovereignty is one consideration among several that drive AM adoption, alongside lead time reduction, price competitiveness, lean maintenance management, design optimization for geometries unreachable by conventional methods, and greener manufacturing. This broader value proposition is consistent with how AM's role is framed across the empirical material in Sections 4.1.2 and 4.1.3.

Respondent 3, project leader for the AM Center initiative, underscores this shift toward national energy security: “The world is changing and we are going from just thinking about sustainability to prioritizing resilience. Having the ability to print a critical part on-site means we are independent of political situations or shipping disruptions in other countries. It is a sovereignty issue for Swedish energy supply”. (Respondent 3)

Despite the strategic importance of sovereignty, the current process of identifying parts for AM is often a reactive response to external supply chain failures rather than a proactive choice. When standard procurement channels fail or lead times become critical, the procurement department must turn to engineering specialists to evaluate alternative manufacturing routes. Respondent 13, a senior procurement specialist at Ringhals, describes the operational challenges of this reactivity: "What we have requested is better foresight to be able to work with the need before it becomes an actual failure. Today we are often reactive, which puts us in a worse negotiating position against suppliers" (Respondent 13)

4.1.1 Price and Monopoly

The market for nuclear spare parts is characterized by respondents as a definitive *seller’s market*. Because many systems are unique and require specialized qualifications, Original Equipment Manufacturers (OEMs) often maintain a monopoly position. Respondent 13 notes that Vattenfall is often forced to accept existing price structures because no viable alternatives exist. They further explain that prices for legacy components have risen significantly in recent years, far exceeding standard inflation indices, as suppliers leverage the critical need to avoid downtime.

This economic pressure is particularly evident in obsolescence management. Respondent 7, an obsolescence management specialist at Ringhals, highlights how extreme pricing can trigger the search for alternative manufacturing:

> We have seen examples where a manufacturer wants 250,000 SEK for an IP converter just because it is an old design they don't really want to manufacture anymore. We can find a modern replacement for 6,000 SEK, but then the cost of rebuilding the system is added. In such cases, we may consciously choose to call a part obsolete to justify developing our own solution. (Respondent 7)

In this light, AM is viewed not just as a technical solution, but as a commercial lever to challenge monopolies and pressure the external market. By establishing the capability to print parts on demand, Vattenfall creates a deterrent against unreasonable pricing. Procurement specialist, Respondent 13, agrees with the analogy that AM capacity acts like a security sticker on a house, the mere knowledge that an alternative exists can prevent overstepping in pricing, even before production begins:

> That alone will result in, I believe, a quite significant saving. Because it will mean that they won't be able to raise [prices] in the same way, and we always have the option to bring out that possibility. (Respondent 13)

Respondent 6, a procurement expert at Forsmark, confirms this *locked-in* status. They explains that suppliers are keenly aware of the regulatory and safety frameworks that limit Vattenfall's purchasing flexibility: “They know we are somewhat locked in, and for good reason. We are governed by operational safety requirements, tied to our documentation and regulatory frameworks.” (Respondent 6)

They add that safety should never justify excessive pricing:

> Just because we require good quality and must always have what we need, it does not mean suppliers can charge excessive prices. Safety and requirements are never compromised, but that is precisely where you go in and question the price when the market overreaches. (Respondent 6)

4.1.2 Lead-time

In the context of procurement within Vattenfall, lead times represent a critical operational parameter, especially given the organization's role as a systemically important energy provider where maintenance failures directly affect societal stability. The ability to rapidly secure components is closely tied to ensuring safety and adhering to strict maintenance schedules without pushing planned operations forward. During the interviews, managers from the procurement department emphasized the challenges of managing unpredictable lead times and the need for proactivity. Respondent 13, a procurement specialist at Ringhals, describes the vulnerability caused by fluctuating lead times:

> Since lead times fluctuate the way they do, especially given the current state of the world, we’re quite vulnerable, so it’s important to build some form of redundancy by perhaps keeping extra stock on hand or staying ahead of the curve and being proactive, and in some way communicating our needs earlier than we might have done in the past. (Respondent 13)

When lead times cannot be controlled or predicted, operations are forced into a reactive mode, demanding immediate prioritization. This urgency is constantly balanced against the strict safety protocols and documentation checks that must precede the installation of any component in the nuclear reactors. Respondent 6, procurement specialist at Forsmark, outlines how urgent needs are handled and the time required for pre-checks:

> Lead times are often extended by the extensive checks required before a component can be approved. It is not just about maintenance, we often need to involve the design department to verify if materials or standards have changed over time. Sometimes we only discover these changes when we reach out to the market and suppliers inform us of new standards. (Respondent 6)

When components are urgently needed to maintain normal operations, Vattenfall often evaluates whether the internal workshop can be used to manufacture the part instead of relying on external supply chains that suffer from extensive delays. The internal workshop provides a significant advantage in terms of speed because they are located directly on-site and can mobilize almost immediately. Respondent 10, who works with manufacturing preparation, highlights this sharp contrast in lead times between internal and external options:

> An external workshop can have lead times of six to eight weeks just for planning. We can start the next day. But if we have to mill something very complex from a solid block, it takes a lot of time and generates huge material waste. (Respondent 10).

External partners at Framatome corroborate this: for complex components such as pump impellers, traditional casting routes can take up to four years, a figure AM can reduce to under a year (developed further in Section 4.1.3). The ability to radically compress these timeframes is identified as a fundamental mechanism for risk minimization and securing the plant's operational autonomy. By internalizing the capability to produce components on-demand, the organization seeks to move from a state of supply chain vulnerability to a proactive maintenance strategy where critical needs can be met within the narrow revision windows. Respondent 13 summarizes the necessity of this internal capability as an essential safeguard against the failures of the conventional market:

> I believe in the possibility to manufacture spare parts in-house for many different reasons. […] when things actually go wrong, you have the possibility to do something reasonably quickly to rectify a problem. […] It is about risk minimization. (Respondent 13)

4.1.3 Components Obsolescence

The challenge of replacing components within aging nuclear facilities is often compounded by component obsolescence, a state where a part is no longer available on the market because it is too old, the supplier has ceased operations, or the product line has been discontinued. The scale of this issue is significant, with industry averages all the way back from 2008 suggesting that approximately 20% of identifiable plant equipment is considered obsolete (Electric Power Research Institute, 2008). Within the Vattenfall framework, a component is formally deemed obsolete when the Original Equipment Manufacturer (OEM) can no longer supply the part according to its original specifications.

To manage this pervasive risk, Vattenfall utilizes a dedicated Component Obsolescence Team and the Proactive Obsolescence Management System (POMS), which functions as a collaborative global network. Research by Said (2025) highlights that managing obsolescence is not merely a technical task but a predictive one. By using indicators to signal risks at an early stage, the organization can act before a failure affects operational reliability. According to the Westinghouse Electric Company (2024), POMS is a centralized, web-based program designed to identify, manage, and resolve obsolescence issues by connecting a global network of over 200 nuclear power plants. This database allows participants to share data and research solutions for discontinued parts, effectively creating a collaborative platform for nuclear operators to maintain foresight regarding legacy components. Respondent 1 and Respondent 2, who serve as project leads within the Forsmark obsolescence team, describe the database as a critical early-warning system. Respondent 7, an obsolescence management specialist at Ringhals, emphasizes that the objective is to secure material supply to ensure that maintenance activities do not have to be moved in time:

> Our work process for obsolescence management is not about removing everything old, but about securing material supply. We use the POMS database, which provides the current status of our components. If a manufacturer issues an end-of-life notice for a part, we know we have two to three years before it is completely phased out. This timeline allows us to plan for a last-time-buy or start looking into manufacturing the part ourselves. (Respondent 7)

A primary driver of long lead times for obsolete parts is the loss of original manufacturing assets, such as molds for casted components. Respondent 5 from Framatome explains that when an original manufacturer no longer exists or the specific model for a valve body is lost, traditional replacement methods can take years to recreate the necessary quality. This creates a severe bottleneck for operators who need to maintain existing designs without changing the entire system:

> In case the valve manufacturer no longer exists, or in case the model of, the casted body no longer exists. If you consider the time you need to create a new model to manufacture the mold to get the right quality, you need something like almost two to three years to get the valve body. Thanks to AM solutions, you can strongly reduce this lead time. (Respondent 5)

The strategic priority remains a *1-1 exchange*, securing a replacement that is geometrically and functionally identical to avoid the exhaustive re-qualification process required for new designs. However, when parts are obsolete, Respondent 6, procurement specialist Forsmark, notes that the organization is often forced into complex qualification loops as they search for alternative products to fulfill the same safety-critical function:

> If a product is obsolete, then we must follow certain rules if we have to qualify a new product. In such a case, one could look at several different variants since you are [already] qualifying... we must, there it is like in consultation with the technically skilled together with those who know the function in detail. (Respondent 6)

4.1.4 Client Relationships

Within Vattenfall's procurement framework, managing relationships with external suppliers is viewed as a vital parameter given the organization's role as a systemically important energy provider: “It is absolutely an aspect. [...] You have some form of relation with the supplier market [and] it can look different depending on what supplier it is [and] how much you have to do with them.” (Respondent 13)

Beyond standard legal or contractual obligations, experts in the organization emphasize that protecting these long-standing partnerships must be evaluated when considering whether to carry out in-house manufacturing. Vattenfall's legal department further notes that supplier relationships must be considered even where no contractual obligations require it, a point developed in detail in Section 4.1.6.

This balance is clearest when a reduction in purchasing volume affects an established supplier relationship. Respondent 6, a procurement expert at Forsmark, frames this as a relational risk rather than a contractual one:

> If we have a close relationship and a steady volume with a supplier, and that volume is suddenly halved, questions will inevitably be raised. The risk is that when we eventually need their expertise or help, their interest in the relationship will have cooled because we are no longer purchasing at the same scale. They might simply say, 'Well, since you're doing everything in-house now, why should we prioritize you?' (Respondent 6)

4.1.5 Physical Constraints

The technical boundaries for AM at Vattenfall are primarily defined by the build volume of the machinery, the precision requirements of nuclear safety, and the labor-intensive nature of post-processing. While the current strategic focus centers on standard capacities of approximately 250x250x250 mm, many nuclear components far exceed these dimensions, creating a size mismatch that places an upper bound on what can realistically enter the AM candidate pool at this stage of adoption. Industrial-scale AM technologies capable of producing significantly larger components already exist within the broader nuclear supply chain, as Respondent 5 at Framatome confirms, meaning the boundary is one of current organizational capacity at Vattenfall rather than technological impossibility. Capturing the geometry of larger components during scanning is further constrained by line-of-sight limitations, meaning certain internal dimensions cannot be captured optically and must be supplemented by manual measurement. This constraint, and the way it shapes the reverse-engineering workflow, is examined in Section 4.2.

4.1.6 IP-rights

Intellectual Property (IP) rights represent a multifaceted legal parameter for Vattenfall when evaluating the reverse engineering and in-house manufacturing of components. According to Respondent 17, a corporate lawyer at Vattenfall, IP-rights involves different legislations depending on the part in question, covering patents, copyright, design protection, and trade secrets. In practice, the primary step for Vattenfall is to physically locate and inspect the original supplier contracts, some of which date back to the 1980s, to check for clauses that explicitly prohibit reverse engineering or sharing data with third parties. The respondent describes the standard process of handling these inquiries between the legal and procurement departments:

> When they ask 'are we allowed to create a copy of this?', the procurement department fetches the specific contract for that product. That contract is then evaluated to determine whether creating the component in-house is legally possible. (Respondent 17)

Respondent 18, a lawyer at Ringhals, describes the same point of departure but emphasizes that the contract review must look specifically for explicit prohibitions against reverse engineering, not merely for what uses are permitted. The lawyer explains that if a contract defines certain allowed uses of supplier documentation, everything not mentioned is implicitly prohibited: “If it's not expressly permitted, you read it by implication - then we're not allowed to use it for that purpose.” (Respondent 18)

Importantly, Respondent 18 clarifies that the absence of a right to use supplier documentation does not automatically prohibit reverse engineering altogether. If Vattenfall can perform the reconstruction from the physical component it legally owns, without relying on the supplier's drawings, a separate legal analysis must be conducted to determine whether a specific prohibition on reverse engineering exists in the contract.

The legality of creating a replacement part through CAD modeling also depends heavily on the source of the data used during the reconstruction. Respondent 17 highlights that taking physical measurements from a part Vattenfall already legally owns avoids infringing on the vendor's proprietary drawings or protected digital information:

> It comes down to the method used to develop your product. If you independently measure a product that we have purchased and legally own, using our own measurement technology, you are not utilizing the supplier's protected information to create your drawing. You are then in a different position, where essentially, for us, only patents could stand in the way (since design rights are not common) for the typical products we use. (Respondent 17)

Beyond contractual clauses, Respondent 18 underscores that parallel intellectual property protections, particularly patents and design protection, must also be evaluated. These protections have fixed durations of typically 20 to 25 years, meaning that many older components at facilities like Ringhals will have aged out of IP protection entirely, opening a legal path provided that no contractual barriers exist. For components where legal protection does remain in force, the lawyer presents licensing as a viable route forward. Rather than treating an existing IP right as a final barrier, Vattenfall can negotiate directly with the rights holder for a license to manufacture the component internally.

A significant operational challenge identified by Respondent 18 concerns the accessibility of the contracts themselves. Locating legacy agreements, some predating digital record-keeping, can require physical searches through archives, as not all documentation is scanned or easily searchable. This creates a meaningful time cost at the start of any legal review. The respondent estimates that once a contract is in hand, the actual legal assessment may take only an hour or two. The bottleneck is finding the right document in the first place.

To manage this, Respondent 18 advocates for a standardized approach to legal review. By evaluating components per product category or per supplier rather than on a purely case-by-case basis, the organization can build precedents that dramatically reduce the time required for future assessments. A supplier whose contract has been reviewed once effectively becomes pre-cleared for similar component types sourced under the same terms.

If legal boundaries or contracts block a certain reverse engineering path, Vattenfall retains the option to negotiate directly with the supplier for explicit permission. Respondent 17 confirms this has been done before and sees no obstacle to it: “Absolutely, that’s fine. What you ensure then is that the person at the supplier company who approves is authorized to leave such an OK.” (Respondent 17)

Respondent 18 echoes this pragmatic stance and goes further:

> The starting point does not necessarily have to be a ‘no’ until we’ve actually received one from a supplier, someone who holds a protection and who isn't interested. And I find it hard to imagine they wouldn't be, in the end it's often about price. (Respondent 18)

Respondent 17 reinforces this point: “Generally speaking, it should be said that the relationship with the supplier must always be considered even if there are no legal obstacles to carrying out in-house manufacturing!” (Respondent 17)

A final legal consideration specific to the make-or-buy assessment concerns information security. Respondent 18 notes that for certain sensitive components, documentation must not leave the facility at Ringhals, making the use of external manufacturing partners, even legally cleared ones, inappropriate on security grounds alone. In such cases, in-house production is not only operationally preferable but may be the only permissible route. The respondent also observes that from a purely legal standpoint, there is no meaningful difference between manufacturing a component in-house and contracting a third party to produce it according to Vattenfall's own instructions, provided no legal barriers exist. This means that before printing infrastructure is acquired, Vattenfall may already be in a position to validate its legal and qualification framework by working with external AM providers under its own design authority.

4.1.7 Qualifications

Qualification is widely regarded as the most significant barrier to the implementation of new manufacturing technologies within the nuclear industry. While components purchased on the open market arrive with manufacturer certificates and performance guarantees, in-house production necessitates that Vattenfall generates this documentation independently, effectively a *birth certificate*, to ensure facility safety. This task is managed by experts such as Respondent 11, systems and design requirements engineer, and Respondent 12, a structural integrity engineer, who define the safety loads, including seismic activity, pressure surges, and thermal expansion that a component must withstand.

The transition to AM shifts the responsibility of quality assurance from the vendor to Vattenfall's internal engineering groups. To validate the integrity of a printed part, the organization must verify the material properties of the specific "batch" by printing test samples alongside the actual component. Respondent 12 explains that this replaces the traditional supplier certificate:

> With AM, we print test rods in parallel with the component to test the material in that specific batch. If we can show that the material data is 'good enough' according to our analysis, we can approve the part. It's about building our own documentation to replace the supplier's certificate. (Respondent 12)

Respondent 18, approaching the same transition from a legal perspective, is explicit that this shift in product liability makes robust internal qualification systems essential rather than optional: “When you manufacture yourself, you also take on full responsibility for the product. That responsibility shifts when you purchase from a supplier, but when producing in-house, you bear it entirely. And that requires solid qualification systems.” (Respondent 18)

Together, these two perspectives clarify why the qualification process cannot be treated as an administrative formality. It is the mechanism through which Vattenfall formally accepts, and can demonstrate it has accepted, full responsibility for the component it has produced.

A specific documentation challenge raised by Respondent 15 and Respondent 16, QC technical specialists, concerns the structure of material certification for AM parts. In standard procurement, a supplier covers both the chemical analysis and the mechanical properties of the delivered material. This internal validation is governed by joint nuclear industry documents known as KBM (Quality Provisions) and TBM (Technical Provisions). One of the QC-specialists further notes that following these established frameworks is what allows the organization to fulfill government safety mandates: “If we do what is written in KBM and TBM, we fulfill the *the Swedish Radiation Safety Authority's Regulations* for nuclear power” (Respondent 15).

A critical regulatory gap identified by Respondent 15 and Respondent 16 is that neither KBM nor TBM currently contain any provisions for AM. They note that powder cannot simply be read as "filler material" under the existing text, meaning the framework must be formally revised before AM can be governed by it. The timeline for such a revision is uncertain, it depends on when an international standard for AM in nuclear applications is finalized, but both Respondent 15 and Respondent 16 confirm that the update will be required regardless of scope. As one of them observes, the last revision of these documents was in 2021, and revisions can range from minor wording corrections to the addition of entirely new chapters.

The engineering department further notes that Vattenfall already performs independent calculations on all incoming products to guarantee safety, which suggests that AM does not necessarily create new procedural layers but rather redirects existing "double work" into the internal validation of the printed part.

Importantly, QC-experts Respondent 15 & Respondent 16 are skeptical that AM implementation would substantially increase QC's workload. They draw an explicit parallel to in-house workshop production, where the same reservation and qualification process already applies, and suggest AM would follow the same path. Their primary condition is that all technical specifications are resolved and documented before the component reaches the QC team, which mirrors the existing workflow. Respondent 16 further notes that the automated nature of the printing process may reduce some of the uncertainty present in traditional manufacturing, since the machine eliminates the human variable that exists when a welder works manually:

> It becomes almost more controlled actually, because the machine is what it is. You remove the human factor, as long as the setup is correct, the process is more consistent

> than having someone welding in a corner. For us, I don't think it changes that much. We still have the same controls to perform. (Respondent 16)

4.1.8 Workshop capability as a manufacturing alternative

The internal workshops at Vattenfall's nuclear sites provide on-demand manufacturing capacity for components that are no longer available through standard procurement. For components with straightforward geometries such as spindles, cones, and shafts, traditional subtractive methods like milling and turning are faster, cheaper, and require no new qualification infrastructure. Respondent 7, an obsolescence management specialist at Ringhals, describes where the boundary between workshop production and AM lies:

> It is currently difficult to find many components suitable for AM. Simple parts (spindles, cones) are more efficiently made in a lathe. The most likely candidates for 3D printing are parts with complex shapes that cannot be easily machined, such as pump impellers. (Respondent 7)

As Respondent 10, maintenance engineer, notes in Section 4.1.2, the workshop's primary advantage is speed and proximity: it can begin production far faster than external suppliers. For components within its geometric capabilities, it is therefore the default alternative to external procurement.

The decision boundary between workshop and AM is defined by geometry. Components that conventional machining can reproduce reliably belong in the workshop, while components with complex free-form surfaces or internal channels that subtractive methods cannot achieve are the candidates for AM. Quality control specialists Respondent 15 and Respondent 16 confirm that the documentation pathway for workshop-produced components is structurally identical to that for externally purchased parts, meaning AM would follow the same qualification logic as an extension of the existing framework.

4.2 The Reverse Engineering Workflow for Worn Components

The process of transforming physical and sometimes worn components into functional digital solid models has been identified as a key step toward establishing a digital supply chain at Vattenfall. This task requires interpreting raw scan data to build functional engineering models, which is frequently challenging when original drawings are missing or incomplete. As this multi-stage reconstruction workflow relies heavily on both technical hardware and expert judgment, specific hurdles can arise when converting physical objects into digital files.

4.2.1 3D scanning

3D scanning at Vattenfall is utilized as a high-precision metrological tool to bridge the gap between physical plant components and their digital representations. Unlike traditional photography, the process captures the exact spatial dimensions of an object, enabling technicians to identify minute operational wear or deformations that are otherwise invisible to the naked eye. Respondent 9, a reverse engineering specialist involved in scanning and modeling at Ringhals, emphasizes the high level of accuracy provided by the specialized equipment used in this process:

> We use Zeiss products right now and they have very high accuracy, good tolerances when you do your scans. [...] It's about a hundredth of a millimeter accuracy, so what you get there, well, it is the *truth in reality.* You see it in proportion to what you are actually going to do. (Respondent 9)

To achieve this level of *truth* in the digital model, the handheld 3D scanning process begins by preparing the physical component with target markers, commonly referred to as stickers. These markers act as reference points that allow the scanner to orient itself and accurately capture the part in 3D space. Respondent 4, a design engineer at Forsmark, emphasizes that the placement of these stickers must be unpredictable to prevent the software from losing its track: "As random as possible. There should be different distances, they should not sit symmetrically because then the scanner can start to confuse them" (Respondent 4).

This makes it possible to rotate and flip the product without the software losing track of its dimensions. Once the component is prepped, the technician scans the object while being connected to a computer that generates the surface mesh model live. However, achieving a high-quality capture involves navigating physical and environmental constraints, as mentioned earlier the scanner requires a clear line of sight and can be heavily affected by shiny surfaces or difficult lighting. Respondent 4 outlines some of these distance and accessibility constraints in the field: "The optimal distance is about 3 decimeters from the scanner. It can handle from about two decimeters up to 4-5dm... closer is not possible, which creates limitations in cavities." (Respondent 4). Because of this physical limitation, scanning deep internal cavities or small holes is notoriously difficult because light and lasers cannot easily penetrate them, meaning that technicians must sometimes complete the drawing using manual physical measurements.

The workflow typically requires cross-departmental interaction. While some units perform their own scanning, high-precision tasks are typically referred to specialized scanning teams that utilize precise instruments yielding hundredths of a millimeter accuracy. Respondent 10, who works as a maintenance engineer, notes that the internal workshop acts as a direct feeder of complex cases to these specialized scanning resources:

> There are cases when we cannot go through with the scanning or drawing ourselves. Then we contact the reverse engineering specialists who does the 3D scanning, noting that this part is too complex for construction to draw up, so it is better that we get a 3D model of it. (Respondent 10)

To capture the complete reality of the workflow, some employees are critical or pragmatic regarding the universal application of scanning. For simple and standard parts, traditional workshop processes or manual drafting are preferred because setting up a scanner and converting the surface mesh into a solid CAD model consumes unnecessary time and resources. Respondent 13, a procurement specialist, shares this critical perspective regarding when 3D scanning becomes an inefficient path: "Sometimes it can be said rather the opposite that it is not worth it because it goes much faster to measure it up with a caliper. Because it is such a simple geometry." (Respondent 13). This pragmatic boundary limits 3D scanning primarily to complex components with free-form surfaces that cannot be reliably documented by a traditional measuring tool alone.

The Ringhals plant has historically relied on 2D paper drawings created forty years ago, resulting in a limited 3D CAD library at the facility. 3D scanning provides a practical method to bridge this gap by capturing physical dimensions directly from existing components. Respondent 8, a reverse engineering specialist at Ringhals, explains what scanning reveals that conventional measurement cannot:

> When we compare nominal dimensions and tolerances against scan data, we see much more than a simple measurement. We can identify deviating trends in a radius, determine if a component is undersized, or detect if it has become oval. You simply get much more actionable information by scanning it. (Respondent 8)

Precise scan data establishes a significant advantage for the subsequent reconstruction phase. Respondent 9, a reverse engineering specialist involved in scanning and modeling at Ringhals, explains that when technicians have exact measurements to work from, the reverse engineering process becomes more reliable because interpretive decisions about geometry and wear can be grounded in accurate baseline data rather than estimation.

When taking part in a scanning process at RISE, the scanning expert Respondent 14, where a Zeiss Hawk 2 scanner is used in practice, describes the setup procedure in detail. Before any component is scanned, the scanner must be calibrated in a two-minute sequence, and the room temperature must be manually entered, a step that may seem minor but directly affects how the scanner reads the material's surface. Respondent 14 emphasizes that the technician must actively watch the live rendering on screen to identify which surfaces have insufficient data points and move the scanner back and forth over those areas until they are evenly covered.

4.2.2 Reverse Engineering

Reverse engineering is the act of recreating the original, intended geometry of a part rather than merely replicating its current, degraded state. Two reverse engineering workers at Vattenfall, Respondent 8 and Respondent 9, explain that this process requires significant engineering art to distinguish between operational wear, such as erosion or corrosion, and the actual design intent of the component:

> We bring the mesh into CAD as a template. Then we start drawing the 'clean' geometry on top. We look for center axes, planes, and symmetries. If a hole has become oval due to wear, we model it as round again based on how we believe it was intended. This is where engineering art comes in, you have to know what is wear and what is design. (Respondent 8)

The technical workflow involves manually transforming a surface mesh into a functional, parameterized solid model. Respondent 4, a design engineer at Forsmark, notes that while the scan provides a visual guide, the engineer must use the CAD environment to build the component from scratch using geometric building blocks to ensure it is ready for manufacturing.

> You can take [the mesh] directly into the modeling, the CAD program, into Inventor. And then you can, so to speak, build the model along this mesh... [but] what you get out is still just basic building blocks that you then have to transfer to the other software. (Respondent 4)

Where scanning cannot reach, traditional tools remain essential to complete the digital model. Respondent 4 describes how this plays out in practice: "You scan as much as you can, then you have to go in and measure certain things. If you have the depth of a hole that you need to know, then you have to use a caliper." (Respondent 4)

The transition from a raw scan mesh to a finalized CAD file is identified as a primary technical bottleneck in the process. Respondent 14 at RISE explains that the mesh file produced by the scanner is not a vectorized mathematical model, which is the format ultimately required for 3D printing. Instead, it functions as a visual scaffold that the engineer must use as a reference to manually construct the CAD file on top of. A critical step in this reconstruction is locking the model to a geometric plane by selecting two reference points to define a symmetrical axis through the component, establishing a stable coordinate system from which the irregular polygon surfaces of the mesh can be reliably interpreted:

> But here is a technical bottleneck, it is not a vectorized mathematical model, which is what you need to actually print. You use the mesh as support and outline to create the CAD file, and you need to lock your model in a plane before you can work with the surface points reliably. (Respondent 14)

Final validation requires *detective work* to ensure the new model aligns with critical system tolerances and surrounding fits. Respondent 4, design engineer, describes the final stage of reverse engineering as a collaborative effort to verify that the reconstructed part will fit perfectly within existing assemblies and meet all safety standards:

> Then it becomes somewhere a bit of detective work to try to find out if there are any fits that need to be checked, if it's against some gasket... or if it's a cone inside a valve that should fit into something. (Respondent 4)

4.2.3 Validation of Components

Another method used in the reverse engineering workflow involves printing the component and then scanning it again to validate the physical output against the original digital models. This allows technicians to see visual representations of any geometric deviations that accumulated during the reconstruction or manufacturing process. Respondent 4 explains how the comparison software works to visualize these microscopic differences:

> You bring a model into the software and then you bring in the scan and lay them over each other and see how much they differ, and you get a color map over the model. Showing how many hundredths of a millimeter differ where. (Respondent 4)

Respondents 15 and Respondent 16 at Ringhals are unequivocal that a physical product is required before QC approval can be granted. Respondent 15, QC technical specialists, adds that certain components will also require additional testing such as pressure testing, weld inspection, or balancing checks, depending on their function and safety classification. This physical gate in the validation process means that even a perfectly reconstructed digital model must still pass through an inspection cycle before it can be installed, a timeline that those advocating for rapid AM deployment must account for:

> We do visual and dimensional inspection, and that feels quite difficult to do if the product isn't physically in your hands. It can say one thing on paper but reality doesn't always look that way. And then we may need to perform certain tests on the final product as well. So no, we would need the final product in hand before we can approve it. (Respondent 16)

For parts that are identical 1:1 copies of available documentation, the approval and calculation process is greatly simplified. However, if the component lacks exact historical material certificates or represents a change in the original design, a new evaluation of how it affects the larger system is required to maintain the facility's safety margins. Respondent 11, systems and design requirements engineer, notes the distinction between using available spares and entering full engineering evaluations: "Is it a maintenance measure that maintenance can fix directly, say we have exactly this valve in storage, then they solve it themselves. Then it never comes to us." (Respondent 11)

4.3 Digital Integration and Information Security: Organizational Attitudes and Structural Barriers

The path described in Sections 4.1 and 4.2 ends at what should be the most straightforward step: sending a validated digital model to a printer and producing a component on demand. But that final step rests on an assumption that has so far been left largely unexamined, that once a validated 3D model exists, the infrastructure required to store, retrieve, and share it will simply be in place. This section examines that assumption. What the empirical material reveals is not a technical solution waiting to be implemented, but a set of organizational attitudes, institutional tensions, and structural constraints that make the question of digital storage and sharing considerably more complex than the vision of an on-demand digital warehouse would suggest. The section begins with the information security framework within which any such system would have to operate, then moves to the organizational attitudes surrounding a shared digital component library, and closes with the institutional conditions that have allowed the infrastructure question to remain unresolved.

4.3.1 The Information Security Architecture at a High-Reliability Organization

Ringhals AB operates its information security framework as a legally distinct license holder and operator under Swedish security protection legislation. Respondent 19 and Respondent 20, security protection strategists at Ringhals, describe the foundational logic of the framework as built around the confidentiality, integrity, and availability dimensions commonly referred to as the CIA triad, to which Ringhals adds traceability as a fourth handling attribute. Every piece of information held or generated by the organization receives an assessment based on these dimensions, and the resulting classification determines the handling rules that apply:

> A body of information, for example a drawing, receives an assessment based on those aspects. And then handling rules are assigned to it. And based on that assessment, confidentiality, integrity, traceability, and availability, the IT security requirements or operational technology security requirements follow. (Respondent 19)

The classification level most directly relevant to plant-related information, including the CAD files and 3D models that AM adoption would produce, is C3, designated as Restricted within Vattenfall's corporate classification. At the corporate level, C3 classified information may be processed using a range of digital tools including SharePoint and AI-based systems. At Ringhals, however, Respondent 19 and Respondent 20 explain that the same classification carries substantially stricter handling rules. C3 plant information is handled within the NSE environment (Nuclear Sweden), a shared IT infrastructure operated jointly by Ringhals and Forsmark, governed by high security requirements and kept logically separated from Vattenfall's broader corporate network. It should be noted that C3 classification as such does not automatically entail the requirements for logical or physical network separation that apply under security protection legislation. Certain information concerning plant design and configuration may nonetheless qualify as security-sensitive under that legislation and require such separation on those grounds. Cloud storage is not permitted for C3 plant information at Ringhals, and SharePoint Online is only sanctioned as a temporary working medium for specific, time-limited projects, with all material required to be purged once the project concludes (Respondent 19 & Respondent 20).

A further dimension of the framework concerns the ownership of information. Respondent 19 explains that plant information belongs to Ringhals AB rather than to Vattenfall as a corporate entity, and that this ownership persists even when information is shared with other parts of the organization. Even information that has been transmitted to Vattenfall centrally remains subject to Ringhals's own handling rules rather than the more permissive corporate standard (Respondent 19 & Respondent 20). This distinction between who physically holds information and who governs it forms the institutional backdrop against which any proposal for digital storage or sharing of 3D models must be understood. The following sections examine what that backdrop means in practice, beginning with the organizational attitudes surrounding a shared digital component library.

4.3.2 The Aggregation Problem: When a Digital Library Becomes a Security Vulnerability

The vision of a digital component library, where thousands of scanned parts are stored and made available for on-demand printing across Vattenfall's nuclear sites, is one that several respondents describe as the natural end goal of AM adoption. Respondent 3, project leader for the AM Center initiative, describes the concept as the logical conclusion of the reverse engineering workflow: a centralized repository where a component can be identified, retrieved, and sent to print without the delays associated with physical procurement (Respondent 3). The information security perspective, however, introduces a dimension of this vision that the broader organization has not yet fully confronted.

Respondent 20 explains that the current practice of sharing individual components between Ringhals and Forsmark is regarded within the organization as relatively manageable from a security standpoint. When a single part is transferred between sites, the exposure is limited: a malicious actor who obtains that file gains knowledge of one component but learns nothing meaningful about how the plant as a whole is configured. The logic changes fundamentally when the scale of sharing increases. As the IT-expert puts it, aggregation is not a concept that standard IT security frameworks typically address, but it becomes the decisive concern as the ambition grows: "The conditions would be created to get a much more complete picture, and a system like that is not something that nuclear power is keen on having in a cloud service with all our plant information." (Respondent 20)

This is what IT-experts refer to as the aggregation problem: the security risk is not a property of any individual file but of the collection as a whole (Respondent 20). A digital library that is comprehensive enough to be operationally useful is, by the same logic, comprehensive enough to constitute a detailed map of the plant's physical configuration. The preferred architecture Respondent 20 describes in response to this problem is an on-premises solution hosted within the NSE environment, the shared IT infrastructure operated jointly by Ringhals and Forsmark, where access is strictly governed and the information never leaves that logically isolated network. In this configuration, individual files could in principle be transferred to an external printing partner on a case by case basis, but the library itself would remain under the direct control of the nuclear sites. Respondent 20 is clear, however, that no such system currently exists, and that building one would require organizational decisions that have not yet been made:

> The best scenario would perhaps be a system that is on-premises. If it were to be hosted by a supplier, we would handle it according to our handling rules. And then we would perhaps need to audit that supplier regarding how they safeguard our information. (Respondent 20)

4.3.3 Cloud Services, Diverging Frameworks, and the Absence of Ownership

The constraints described in the preceding sections do not exist in isolation. They sit within a broader organizational pattern in which the rules governing digital information at Ringhals and those applied across Vattenfall centrally have developed in different directions, creating a structural tension that directly affects the feasibility of any shared digital infrastructure for AM. As outlined above, Vattenfall's corporate framework permits C3 classified information in cloud and AI-based tools, while Ringhals prohibits this entirely. Forsmark applies an even stricter interpretation, disallowing SharePoint Online in all circumstances where Ringhals permits it only as a temporary working medium (Respondent 19 & Respondent 20).

The practical consequence is that centrally developed IT solutions, designed to comply with Vattenfall's corporate classification standard, frequently arrive at the nuclear sites in a form that is incompatible with local security requirements. Respondent 19 describes a recurring structural pattern:

> We have tried for quite a long time to get an explicit statement that nuclear has different handling rules. But it gets pushed down to Ringhals, that we should have it in our local management system. And then Vattenfall IT and all the central initiatives do not have access to our local management system, so they never see the requirement picture. And when we finally get presented with a finished solution, we just get told we are complicated and difficult. (Respondent 19)

This institutional friction has a direct bearing on the question of who owns the problem of designing a secure digital infrastructure for 3D models. IT operations at Ringhals rely on Vattenfall IT as a shared service, meaning that any solution within the NSE environment would still require central IT involvement and resourcing, yet centrally developed solutions do not meet local security requirements (Respondent 19 & Respondent 20).

This gap between where the requirement sits and where the capacity to address it resides is reflected in how the digital warehouse question is perceived more broadly within the organization. Respondent 3, project leader for the AM Center initiative, puts it plainly: “The digital warehouse IT build-out does not really feel like something anyone has a grip on. It is the consequence of everything that comes before it.” (Respondent 3)

This perception, that the IT infrastructure question is downstream of more pressing concerns and therefore deferred, is consistent with the broader organizational pattern that IT-experts Respondent 19 and Respondent 20 describe. At the time of this study, no standardized system exists for the secure sharing of 3D models between Ringhals and Forsmark, no decision has been made regarding the architecture of a future digital component library, and no single function within the organization has been assigned responsibility for resolving the gap between what the AM vision requires and what the current information security framework permits (Respondent 19 & Respondent 20).

5. Analysis and Conclusions

This chapter connects the empirical findings from Chapter 4 with the theoretical framework established in Chapter 2. The analysis is organized around the People, Process, and Technology framework and the three sociotechnical tensions developed in Section 2.4. Tension 1, Stability versus Autonomy, structures the analysis of RQ1. Tension 2, Automation versus Craft, structures the analysis of RQ2. Tension 3, Security versus Scalability, structures the analysis of RQ3.

The chapter presents two practical design proposals. Section 5.1 introduces a seven-gate flag system for component selection, designed to redirect the organization's existing analytical caution toward the supply strategy itself rather than treating it as a barrier to change. Section 5.2 proposes an eight-stage reverse-engineering workflow organized around bounded codification, a design principle that specifies the workflow architecture fully while protecting the stages where procedural specification would reduce rather than improve reliability. Section 5.3 examines the digital infrastructure conditions that both proposals depend on. The two proposals are designed to work together: the flag system determines what enters the reverse-engineering workflow and the workflow converts those candidates into validated models.

5.1 Reconfiguring Component Selection: Designing a Proactive Flag System

This section develops the answer to RQ1 through the lens of Tension 1, introduced in Section 2.4. The tension captures the way the same mindful inertia that makes an HRO reliable also slows its response to supply-chain failure, and it frames the analytical work of the section. Sections 5.1.1 and 5.1.2 diagnose the tension empirically. Sections 5.1.3 through 5.1.5 develop the flag system as the organizational design that reconfigures the tension rather than dissolving it.

5.1.1 The Reactive Baseline and the Monopoly Lock-in

The empirical material in Sections 4.1.1 through 4.1.3 describes a procurement function that operates predominantly in reactive mode. Needs are registered in the internal enterprise system when maintenance staff identify wear during revision windows. Only once a part proves unavailable or catastrophically expensive does procurement escalate to engineering for evaluation of alternatives. Respondent 13, a procurement specialist at Ringhals, captures the operational cost of this pattern precisely: "we are often reactive, which puts us in a worse negotiating position against suppliers". Respondent 7's account of a supplier quoting 250,000 SEK for a legacy IP converter against a 6,000 SEK modern equivalent demonstrates the pricing power that the reactive posture hands to Original Equipment Manufacturers who hold regulatory-qualified positions. Respondent 6, a procurement expert at Forsmark, remark that suppliers “know that we are somewhat locked into things” confirms that this pricing logic is not accidental. It is a strategic response by OEMs to the structural constraints under which Vattenfall operates.

Read through the theoretical lens developed in Chapter 2, however, this is not most usefully understood as procurement inefficiency. Ford's (2018) analysis of how obsolescence becomes organizationally invisible predicts exactly this drift. When aging components are administratively reclassified from safety concerns into routine procurement problems, the preoccupation with failure that Christianson et al. (2011) identify as central to high reliability is quietly eroded. Information about component repairability becomes buried in legacy documentation and in the tacit practice of *making do* (Ford, 2018), and the organization loses the analytical sensitivity that would allow it to detect latent risk before it forms as a supply crisis. The reactive pattern Respondent 13 describes, combined with POMS providing warnings two to three years before a component disappears from the market, suggests that the signal exists but the organizational routines for acting on it have not kept pace with the growing scale of the problem.

Gholipour et al.'s (2025) treatment of reactive maintenance provides the second theoretical link. Reactive maintenance appears inexpensive in the short term because it defers costs that are not yet billed, but in capital-intensive sectors the deferred costs compound into what Gholipour et al. describe as maintenance debt. The extortionate pricing that Respondent 7 and Respondent 6 report is the financial face of that debt, and Respondent 13's observation that prices for legacy components have risen far beyond standard inflation is best understood not as market variance but as interest collecting on a debt that Vattenfall's mindful inertia has prevented it from servicing. The organization's deliberate caution toward unanalyzed change (Pettersen and Schulman, 2019), a caution that functions as intended in the reactor hall, transfers without modification to the procurement boundary, where it produces the opposite of its intended effect. LaPorte and Consolini (1991) describe the rigidity of HRO as an organizational immune system, built to keep unvalidated changes from destabilizing operations. In the reactor hall, this immune system functions exactly as designed. But in the procurement context, it has not recalibrated to recognize that the main source of risk is no longer a change being pushed in from outside. The same caution that protects the reactor hall has not been reconfigured to recognize that the principal risk now accumulates from within, as aging components lose their supply base and sourcing channels grow more expensive and less reliable.

This framing reconstitutes Research question 1 at the analytical level. The reactive pattern is not a deficit to be corrected through better procurement discipline. It is the predictable output of a mindful-inertia regime applied to a decision context where the external market has become the principal source of risk. The question of how component selection should be configured for AM therefore cannot be answered in narrow procurement terms. It has to be answered as a question about how mindful inertia itself can be redirected. This is not a procurement failure that better discipline would correct. It is the predictable output of a mindful-inertia regime that has not yet been reconfigured to treat external-supply dependency as the reliability risk it has become. That reconfiguration is what Tension 1 demands, and it is what the flag system developed in Sections 5.1.3 through 5.1.5 is designed to deliver.

5.1.2 Sovereignty, Resilience, and the Case for Design-out Maintenance

The empirical material does not merely support the case for AM adoption. It provides a specific justification for why continued external-supply dependency has become strategically indefensible for an organization in Vattenfall's position. Respondent 3's, project leader for the AM Center initiative, framing of the project, that the world is shifting from sustainability toward resilience, and that on-site print capacity converts political and logistical exposure into operational autonomy, is not a rhetorical addition to the AM business case but the organizing rationale for it. Respondent 5, the expert at Framatome, a French nuclear component manufacturer, reinforces this from the supplier side. The shrinking of European nuclear foundries and the geographic concentration of alternatives in Asia has made sovereignty over the component supply chain a policy-level concern, and AM is presented as one of the few available routes to a sovereign manufacturing alternative for specific use cases.

Holmström et al. (2010) identify low-volume, high-variety, time-critical components, precisely the profile of obsolete nuclear spares, as where rapid manufacturing generates the clearest value. Critically, they locate that value not in the equipment itself but in the surrounding workflows for candidate identification. This makes the handoff between component identification and engineering evaluation at Vattenfall the principal site where AM either delivers or falls short.

Gholipour et al.'s (2025) concept of Design-out Maintenance extends the argument. Rather than merely managing failures after they occur, Design-out Maintenance seeks to eliminate the need for maintenance through improved design, and, in the present context, through reducing the external-supply dependency that shapes how every obsolete-component replacement is sourced and priced. In-house AM capacity is the technical condition for this reduction, but the condition is not sufficient. The flag system developed in the next subsection is the organizational mechanism that converts capacity into Design-out Maintenance at the point of decision.

A further aspect of the empirical material shows that the value of AM capacity is partly that of a commercial counterweight. Respondent 13, a procurement specialist at Ringhals, captures this logic through an analogy: the mere existence of an in-house AM capability acts like a security sticker on a house, discouraging suppliers from unreasonable pricing even before a single component has been printed. Respondent 6, a procurement expert at Forsmark, reinforces the point from the negotiating side, noting that safety requirements should never be used to justify usury prices. Holmström et al.'s framework accommodates this logic. They suggest that rapid manufacturing capability can reshape the economics of an entire spare-parts network, not only the components actually printed. If that holds in practice, the case for AM investment extends beyond what will be produced to what may never need to be produced, because the capability itself may moderate how suppliers price and prioritize their remaining customers. This is a plausible rather than a guaranteed effect, but it is grounded in the commercial dynamic that several respondents independently describe.

Every argument developed in this section converges on the same conclusion. The stability that Vattenfall's operational logic is built to protect is increasingly undermined by the external-supply dependencies that the same logic has allowed to accumulate. Resolving Tension 1 does not mean choosing between stability and autonomy. It means building the organizational mechanism through which the pursuit of autonomy operates within the same analytical structure that HRO stability requires. The flag system developed in the next section is that mechanism.

5.1.3 Designing the Flag System: Structure, Priority, and Gatekeeping

The empirical material points consistently toward a specific organizational problem. Components enter consideration for AM reactively and are evaluated through ad-hoc consultations between procurement, engineering, and legal, with no structured sequence. The flag system proposed in this section puts into practice Holmström et al.'s (2010) requirement for workflows that identify candidate components, applying their recommendation within the specific procedural constraints that Pettersen and Schulman (2019) identify as characteristic of HRO governance.

The system is structured as a sequence of categorical gates, each corresponding to a distinct class of constraint surfaced in Chapter 4. A component enters the AM candidate pool only when it has been flagged green by every gate, and the order of the gates matters. Gates are sequenced so that each gate resolves a constraint whose violation would make downstream work wasted.

Gate 1: Legal and IP review

The legal gate comes first because its failure makes all subsequent work wasted. As Respondent 17, a corporate lawyer at Vattenfall, describes in Section 4.1.6, legality depends on whether contracts prohibit reverse engineering, whether reconstruction relies on the supplier's protected drawings or on independent measurement of owned components, and whether direct negotiation has taken place. Respondent 18, a lawyer at Ringhals, adds that the practical bottleneck is rarely the assessment itself. Once a contract is in hand, they estimate this takes only one to two hours but the issue is locating the document. Legacy agreements predating digital record-keeping may require physical archive searches. To manage this cost, Respondent 18 advocates reviewing contracts per supplier or product category rather than case by case, so that a cleared supplier becomes pre-cleared for similar components under the same terms. Their broader assessment matters for how the gate is communicated internally: in the cases they have reviewed, no explicit prohibition against reverse engineering has been encountered. Gate 1 is therefore less a barrier than a structured process for identifying what is required to proceed, and one whose cost decreases over time as category-level precedents accumulate.

Respondent 18's argument for category-level review points toward a broader logic that runs through the flag system as a whole. A gate decision made once for a supplier or product category does not need to be made again from scratch, and this principle extends beyond the legal gate: the system accumulates reusable knowledge with each component that passes through it, reducing the cost of operating across legal, qualification, and commercial dimensions alike.

Gate 2: Qualification and regulatory feasibility

The qualification gate asks whether a viable documentation route exists under the current regulatory framework. As Respondents 15 and Respondent 16 note in Section 4.1.7, the joint industry documents governing material qualification at Swedish nuclear plants, the KBM and TBM standards, do not yet contain provisions for AM. For some components, this means the qualification pathway does not yet exist regardless of technical suitability. This gate filters those components out and places them on a regulatory watchlist, so that when the standards are updated, the organization already knows which components are next in line. Gate 2 also encodes the simpler filter that Respondent 11, systems and design requirements engineer, identifies: a component that maintenance staff can resolve directly using existing stock does not belong in the AM pipeline regardless of its qualification status. The gate is therefore both a regulatory check and a basic triage step.

Gate 3: Physical feasibility

This gate checks whether the component can actually be produced within the current build-volume limits, tolerance requirements, and post-processing capabilities available to Vattenfall. The constraints documented in Section 4.1.5 set real limits on what is achievable internally at acceptable quality. A component that clears the legal and qualification gates but exceeds the current build-volume capacity of approximately 250x250x250 mm is not an AM candidate at this stage. As Section 4.1.5 establishes, however, this boundary reflects current organizational capacity rather than technological impossibility, since industrial-scale AM technologies capable of producing significantly larger components already exist within the broader nuclear supply chain. Gate 3 should therefore be understood as a dynamic filter whose boundary moves as Vattenfall's own production capacity develops, rather than a permanent exclusion of larger components from the AM candidate pool.

Gate 4: Workshop-alternative assessment

As Respondent 10 and Respondent 7 both note, simple parts like spindles and cones are more efficiently produced on a lathe. AM is not always the right answer even when it is technically feasible. This gate defines an efficiency boundary: components with straightforward geometries that the internal workshop can produce faster and more cheaply should stay in the workshop. AM candidates at this gate are components with complex shapes or geometries that conventional machining cannot reliably reproduce.

Gate 5: Obsolescence and supply-risk status

This gate draws on the supply-risk data that POMS provides, as described in Section 4.1.3. Components that manufacturers have flagged as nearing discontinuation, with a remaining market window of roughly two to three years, are priority candidates for the AM pipeline. Components showing early signs of supply-risk but not yet approaching discontinuation are placed on a watchlist for review at the next revision cycle. Components still reliably supplied by their original manufacturer are generally lower priority, since the qualification investment is harder to justify when conventional supply remains stable. These are not permanently excluded but deferred to a future review.

Gate 6: Commercial assessment

This gate weighs two considerations. The first is price deviation. Cases like the 250,000 SEK IP converter described by Respondent 7 in Section 4.1.1, where AM development is justified on purely economic grounds, clear this gate straightforwardly. The second is supplier relationship. As both Respondent 17 and Respondent 6 at Forsmark note in Sections 4.1.4 and 4.1.6, moving a component to in-house production has downstream effects on the broader supplier relationship, even when no single transaction is legally or commercially problematic. This gate does not block such components from the pipeline but flags them for a more careful discussion of timing and communication with the affected supplier.

Gate 7: Lead-time criticality

The final gate compares two timelines. The first is the external supply lead time. External workshops often carry planning phases of six to eight weeks, according to Respondent 10, while casting lead times for complex components like pump impellers can reach four years, as Respondent 5 at Framatome reports. The second is the component's replacement window, meaning how quickly a failure would force a revision delay or production loss. This gate clears when the AM route offers a meaningful reduction in lead time relative to conventional sourcing, even if it does not close the gap entirely. The gate also introduces a timing caveat. The flag system is designed as a proactive instrument and its full value is realized when components are assessed well before a crisis forces the decision. When time pressure is acute, some gates may be assessed simultaneously rather than strictly in sequence, though the legal gate should always produce a clear assessment before any in-house production work is commissioned.

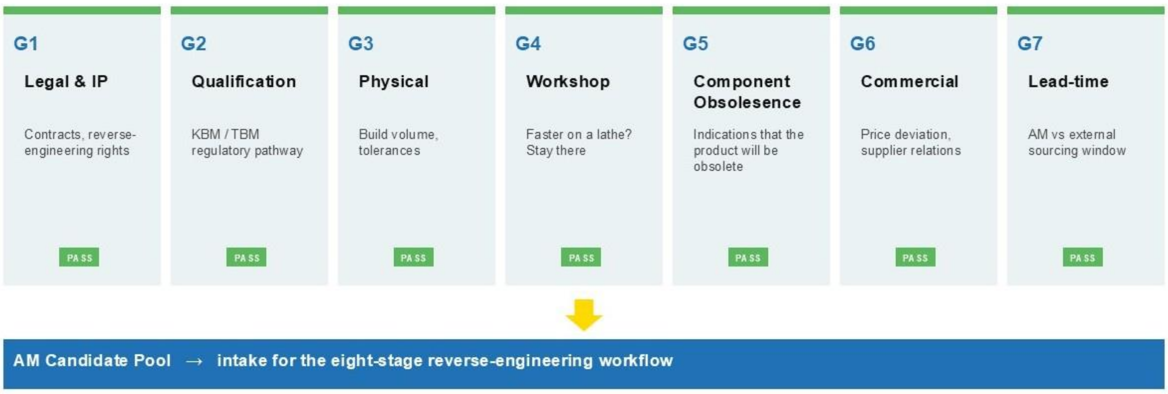

Figure 5.1. The seven-gate flag system for identifying and prioritizing components for Additive Manufacturing. Gates are sequenced so that each resolves a constraint whose failure would invalidate downstream work. A component enters the AM Candidate Pool only when flagged green by all seven gates, at which point it becomes intake for the reverse-engineering workflow developed in Section 5.2.2.

What matters theoretically is not the specific list of gates but the structural logic behind them. Each gate targets a specific category of risk that, if missed, would make all downstream work wasted. This reflects the HRO principle that Christianson et al. (2011) call preoccupation with failure, the institutional habit of asking what could go wrong before committing to a course of action. The flag system does not bypass this habit. It reproduces the same logic of categorical evaluation and cross-functional sign-off that governs every other operational decision in the organization, but redirects its output. Instead of filtering out every departure from the installed-base status quo, the system filters in the specific components where departure is strategically warranted.

This is the central theoretical claim of this section: the flag system does not displace mindful inertia, it extends it. The same analytical caution that Vattenfall already applies to every proposed change to the installed base is here applied to the supply strategy itself. What changes is not the standard of analysis but the question being analyzed. This matters for the broader literature on HRO adoption of new technologies, because it suggests that organizational rigidity need not be overcome or bypassed for adoption to proceed. It can instead be redirected.

5.1.4 The Data Foundation Problem

The flag system depends on two preconditions that sit outside its gate structure. The first is data quality. Component records in the internal enterprise system must be clean and searchable enough to support systematic screening, and the contract archive must be indexed by supplier and product category so that the legal gate can operate at scale rather than case by case. The second is departmental participation. Each gate encodes expertise that resides in a distinct function, and the system cannot be run by a dedicated AM office alone. Both preconditions are addressed in turn in the section that follows.

Respondent 1 and Respondent 2, who manage the obsolescence database at Forsmark, identify data quality as a significant practical barrier. A component entered into the system twenty years ago with an incomplete description or a typo becomes difficult to locate in a digital search today. Across tens of thousands of records, these small registration errors accumulate into a search environment where systematic screening becomes unreliable. Ford's (2018) analysis connects this directly to the reliability risk: when component information is unreliably recorded, the signal exists but cannot be acted on. Respondent 18 identifies a structural parallel in the contract archive, where legacy agreements that have never been digitized can require physical archive searches before a legal assessment can begin. Both problems have the same consequence for the flag system. The obsolescence gate is only as good as the data behind it, and the legal gate can only operate at the category level that Respondent 18 recommends if the contracts are findable in the first place. Other gates, particularly the physical feasibility and workshop-alternative gates, can function through direct consultation and expert judgment even when records are incomplete, but the obsolescence gate has no systematic basis without clean underlying data. Leavitt (1964) and Sjödin et al. (2018) are both clear that the three PPT dimensions must be addressed together rather than sequentially. Data remediation is therefore a precondition for the flag system, not a parallel task.

5.1.5 The People Dimension: From Mandate to Organizational Buy-in

Once the data foundation is in place, the flag system depends on the active participation of every functional team whose judgment the gates require: legal, engineering, procurement, quality control, and the internal workshop. Gallivan's (2001) framework for secondary adoption clarifies what this means in practice. Primary adoption, the leadership-level commitment to AM investment, has already occurred at Vattenfall. What has not yet occurred is the secondary adoption that Gallivan defines as genuine embedding in daily work. For the flag system to function as intended, it needs to reach at least the routinization stage across every department whose gate it depends on.

A leadership decision to invest in a new technology does not guarantee that it becomes embedded in daily work. Departments may participate at a surface level without genuinely integrating the flagging process into how they make decisions. Pettersen and Schulman (2019) note that HROs place a heavy burden on any new process that claims a share of departmental attention, since every element entering the system must first demonstrate that it does not compromise established safety. The flag system therefore requires deliberate communication. The connection between the flag system and Vattenfall's existing reliability mandate is real at the design level, as argued in Section 5.1.3, but it is not automatically visible in daily practice. Without deliberate framing, departments are likely to experience the flagging process as an additional administrative task rather than as part of their reliability mandate. The argument developed in Sections 5.1.1 and 5.1.2, that external-supply dependency has itself become a principal reliability risk, is what makes this framing substantive rather than cosmetic. The flag system needs to be introduced in language that connects it to Vattenfall's existing safety-culture vocabulary.

Beyond internal adoption, the flag system must account for how in-house manufacturing affects Vattenfall's relationships with external suppliers. Respondent 6, a procurement expert at Forsmark, Respondent 13, a procurement specialist at Ringhals, and Respondent 17, a corporate lawyer at Vattenfall, each describe the tension between bringing manufacturing in-house and preserving the supplier relationships that Vattenfall may still need for components outside what AM can produce. Halving an order volume risks cooling a supplier's interest in the relationship precisely when the non-AM component set still needs it. The commercial gate developed in Section 5.1.3 is directly relevant here. Its distinction between components cleared for immediate production and those cleared but deferred preserves both the commercial pressure on suppliers and the ongoing relationship, without forcing a binary make-or-buy decision before the organization is ready.

A component that passes every other gate may still be deferred because the regulatory framework needed to approve it has not yet been updated. As quality control specialists Respondent 15 and Respondent 16, QC technical specialists, note, the industry standards governing material qualification do not yet include provisions for AM. Tracking these components separately gives Vattenfall a concrete list of cases to raise when the standards revision process begins, rather than identifying them under time pressure after the fact. This distinction also makes the flag system a more legitimate claim on departmental attention, because its output is not a binary make-or-buy decision but a considered position that several departments have actively shaped together.

Infusion, in the deepest sense, would mean that the flag system's outputs shape capital investment and long-range supplier strategy at Vattenfall. When Vattenfall manufactures in-house, product liability does not transfer with a purchase transaction, as the organization instead holds full responsibility from the point of manufacture. This makes robust internal qualification systems not optional but constitutive of what infusion means in this context. The flag system cannot be said to have reached infusion until the full chain from legal gate to quality control sign-off is institutionalized reliably enough to carry that responsibility. That is not where the organization is today, and it defines the horizon that full secondary adoption points toward.

5.2 Codifying the Engineering Art: A Workflow for Reverse-Engineering Worn Components

This section develops the answer to RQ2 through the lens of Tension 2, introduced in Section 2.4. Tension 2 captures the gap between the near-automated narrative surrounding AM and the reality of a workflow that depends on expert judgment at its most critical stages. The organization's ability to routinize and scale AM adoption therefore depends not on better hardware, but on how well it can turn expert craft into a structured and repeatable process. Section 5.2.1 diagnoses this tension empirically. Sections 5.2.2 through 5.2.4 develop the workflow as the organizational design that addresses it, built around the concept of bounded codification introduced in Section 5.2.3.

5.2.1 The Automation Narrative and the Reality of Reverse Engineering

The literature that forms the technical background in Section 2.3 presents AM as a largely automated production route. Abdulhameed et al. (2019) emphasize that the layer-by-layer fabrication process mirrors the geometric specifications defined in the CAD model, requiring minimal human intervention beyond setup and post-processing. This characterization of the printing process itself is accurate: a validated digital file goes in and a physical part comes out, with setup as the primary manual task. What the literature leaves largely unexamined is what it takes to produce that validated digital file in the first place, particularly when the component is worn, original drawings are missing, and the geometry must be reconstructed from physical measurement and expert judgment.

Section 4.2 establishes a reality that differs significantly from this automated narrative. Several respondents describe the workflow's dependence on expert judgment from different vantage points. Respondent 8 and Respondent 9, reverse engineering specialists who carry out this work, describe the reconstruction of a worn component's geometry as engineering art, where the central task is distinguishing operational wear from design intent. Respondent 4, a design engineer at Forsmark, identifies a separate constraint: scanning is fundamentally limited by line of sight, meaning internal cavities and deep holes cannot be captured optically and must be supplemented by manual measurement. Respondent 14, a scanning expert at RISE, identifies the transition from a scanner-produced mesh to a vectorized CAD model as a bottleneck that cannot be automated, because the mesh is a surface approximation and converting it into a solid model requires the engineer to establish geometric reference planes through deliberate choice.

Respondent 4 further describes the final validation stage as detective work, where the engineer must trace which fits, gaskets, and tolerances the reconstructed part must respect. Expert judgment therefore enters at the start of the workflow, at the transition between digital stages, and at the point of physical verification.

This empirical picture has a direct theoretical consequence that shapes how the workflow proposed in Section 5.2.2 is designed. The deployment of a technology whose theoretical identity is automated and digitally native depends in practice on forms of expert judgment that resist the codification automation assumes. Gallivan's (2001) stages of secondary adoption presuppose that an innovation can be progressively routinized into normal organizational activity, but routinization requires that the underlying work can be specified in transferable, teachable form. Where that work depends on tacit expertise in Nonaka's (1994) sense, meaning knowledge rooted in individual experience and situated judgment that resists full articulation, routinization either stalls or must be approached selectively: codifying what can be codified, identifying the stages where codification would remove the judgment that makes the work reliable, and treating the distinction between the two as the design principle of the workflow itself.

5.2.2 A Proposed Reverse-Engineering Workflow

Before describing the stages of the workflow, the three codifiability levels referred to throughout this section need to be defined. Each stage is assigned to one of these levels based on how fully its internal operations can be specified in transferable, teachable form.

A fully codifiable stage contains operations that can be written down as a Standard Operating Procedure, meaning a step-by-step instruction that any trained technician can follow and whose correct execution can be verified afterward. The work at these stages is the same regardless of which technician performs it, and full specification improves rather than harms reliability. Scanner calibration sequences and dimensional checklists belong here.

A partially codifiable stage allows for the specification of boundary conditions, thresholds, and acceptance criteria, but its execution within those bounds requires tactical judgment acquired through experience rather than through instruction. The procedural framework can be written down, the moment-to-moment decisions made inside that framework cannot.

A tacit stage contains operations that resist procedural specification altogether. The workflow specifies what enters and exits these stages, what the expert produces, and how the output is documented for the auditable record. It does not specify how the internal judgment is exercised, because that judgment depends on situated reading of the specific component and cannot be prescribed in advance. In Nonaka's (1994) terms, these are the operations whose tacit content cannot be externalized without removing the very discretion that makes the work reliable.

These three levels are not arranged in a hierarchy of value. Each level is appropriate to a particular kind of work, and the design principle of the workflow is to match each stage to the level that fits the operation it contains. The eight stages of the workflow are now described in turn, with each stage's codifiability level stated at the start of its description.

Stage 1: Component intake. A component enters the workflow through the green-flag output of the system developed in Section 5.1.3. The reverse-engineering team does not make its own decision about which components to take on. The flag system delivers a component whose legal, qualification, physical, workshop-alternative, obsolescence, commercial, and lead-time gates have all been cleared, together with the documentation produced by each gate. The intake stage is fully codifiable because it consists of receiving a defined input rather than evaluating it. The team confirms that the handoff package is complete and logs the component into the workflow, after which the operational stages begin.

One implication of the legal analysis in Section 5.1.3 is worth noting here. Because there is no meaningful legal distinction between manufacturing in-house and contracting an external AM provider working under Vattenfall's own design authority, the organization can initiate and validate this workflow, including its qualification documentation, before any printing infrastructure has been acquired. The capital decision does not need to come first.

Stage 2: Preparation and setup. The preparation stage readies the scanner and the component for capture. Respondent 14's account at RISE specifies the substantive content. A two-minute scanner calibration sequence runs first, followed by manual entry of room temperature into the scanning software, because the measurement is sensitive to thermal variation in the scanned surface. Positional reference markers are then placed first on the surrounding table to establish spatial context and afterwards on the component itself. Respondent 4's guidance on marker placement, that the pattern must be as random as possible, with varied spacing and no symmetries, ensures that the scanning software does not confuse markers with one another. Every operation at this stage can be rendered as an explicit Standard Operating Procedure whose adherence is verifiable.

Stage 3: Scanning. The scanning stage is where the component's geometry is captured into a mesh cloud. Several aspects of this work admit explicit specification. Minimum point density, maximum surface-coverage gaps, and acceptance criteria for the mesh output can be defined in advance. The software functions of the scanner, including the dedicated hole-scanning mode that adjusts the scanner's angle to capture recessed geometry, follow deterministic operating instructions.

What the procedure cannot capture is the technician's reading of the live rendering during the scan itself. Respondent 14 from RISE emphasizes that the technician must actively monitor the screen to identify under-covered surfaces and re-traverse them until the point density is sufficient. Recognizing which surfaces typically fail to capture cleanly, which areas need a second pass, and how the geometry of a particular component will interact with the scanner's optics depends on accumulated experience rather than on procedural instruction. Reflective surfaces, deep recesses, and sharp internal edges all behave in ways that an experienced technician learns to anticipate. The scanning stage is therefore partially codifiable. Its boundary conditions and acceptance criteria can be written down, but the tactical judgments made within those boundaries belong to the operator.

Stage 4: Manual supplementation. Because the scanner cannot capture deep internal cavities or hidden holes, certain measurements must be taken with traditional tools. Respondent 4's reference to the caliper is the canonical case. The manual supplementation stage handles these gaps systematically. For each component class, the set of features that scanning cannot reliably capture is enumerated in advance, and the supplementation routine specifies which tool is used for each feature and what tolerance is acceptable. The stage is fully codifiable as a checklist, because the work consists of measuring known feature types with known tools to known precision requirements.

Stage 5: Mesh to CAD transition. The transition from mesh to CAD is identified by Respondent 14 at RISE as the workflow's principal technical bottleneck. The scanner output is not a vectorized mathematical model suitable for manufacturing. It is a polygon-cloud approximation of the scanned surface. Conversion requires the engineer to select two reference points through which a symmetry plane can be established, locking the model to a stable coordinate system from which the irregular polygon surfaces can be interpreted into geometric primitives.

This stage is tacit in Nonaka's (1994) sense. The general protocol for establishing a symmetry plane can be described, and the software operations for attaching that plane to a coordinate axis can be documented as a standard procedure. What cannot be reduced to procedure is the choice of which two reference points are the right ones for the particular component. The choice depends on the engineer's intuition about which aspects of the scanned surface are reliable and which are corrupted by scanning artefacts or by the wear that motivated the reverse-engineering exercise in the first place. The workflow protects this operation from premature procedural specification and documents only that the choice was made and what its outcome was.

Stage 6: Reconstruction. The reconstruction stage is the engineering-art core of the workflow. It involves the manual reconstruction of the component's intended geometry on the scaffold of the mesh. Respondent 8 and Respondent 9’s description of this work captures the central judgment. They look for center axes, planes, and symmetries, and they model a worn hole as round again based on how they believe it was intended. The judgment at stake here concerns design intent rather than measured reality, and it draws on the engineer's familiarity with how this class of component was originally manufactured and how it typically wears.

Of all the stages in the workflow, this is the one most resistant to codification, and the workflow protects it rather than attempting to reach Standard Operating Procedure. What the stage produces, a CAD model intended to represent the original design rather than the worn artefact, can be documented and audited. How the engineer arrives at that model cannot be prescribed in advance. The workflow records the inputs, outputs, and decisions taken at this stage and leaves the internal operations to the expert.

Stage 7: Digital validation. The reconstructed CAD model is overlaid on a rescan of a test print, and any geometric deviations are mapped to the hundredth of a millimeter. The stage is fully codifiable: acceptance criteria can be specified in advance, the software operations are deterministic, and the output is a documented deviation map that forms part of the component's qualification record. This provides a geometric checkpoint before the component moves to physical inspection.

Stage 8: Physical validation and quality control. The final stage is physical validation and QC handover. Respondent 16 is unequivocal that a physical product is required before QC approval can be granted. Visual and dimensional inspection cannot be performed on a digital file, and certain components require pressure testing, weld inspection, or balancing checks that only apply to the printed artefact in hand. Respondent 15 and Respondent 16 observe that the documentation pathway for AM components is structurally identical to that for externally purchased parts, with the specific difference that material certification is split into a chemical-composition certificate for the input powder and a mechanical-properties certificate derived from batch-printed test bars. The test-bar protocol Respondent 12, a structural integrity engineer, describes is the AM-specific addition.

Although the documentation route is specifiable, the validation work itself is tacit. QC inspectors read each physical component against its drawing, and the discrepancies between paper and reality that Respondent 16 refers to are not predictable in advance. Whether a particular weld passes inspection, whether a balancing check uncovers a fault, and whether a pressure test reveals an unforeseen weakness are judgments made on the artefact in hand rather than procedures executed against the digital file. The workflow specifies that the QC team performs the inspection and what the documented outcome is required to contain, and it leaves the inspection itself to the inspector.

Respondent 18 adds a legal dimension that reinforces why this stage cannot be compressed. When Vattenfall manufactures in-house, product liability does not transfer with a purchase, the organization holds full responsibility from the point of manufacture. The birth certificate that Respondent 12 describes is therefore not only a technical qualification record but the legal foundation on which that responsibility rests. The tacit and legal character of Stage 8 point to the same conclusion from different directions: the physical gate must be passed and its documentation must be complete before any component produced through this workflow can be installed. The eight stages and their codifiability levels are summarized in Figure 5.2 below.

Figure 5.2. Eight-stage reverse-engineering workflow, with codifiability level per stage. Fully codifiable stages: 1, 2, 4, 7. Partially codifiable stages: 3. Tacit stages: 5, 6, 8.

The workflow is built as a staged pipeline where every handoff is documented and traceable, but the stages differ in how fully their internal operations can be written down. Four stages, component intake, preparation, manual supplementation, and digital validation, can be fully codified into step-by-step procedures. One stage, scanning, can be codified in terms of what counts as an acceptable result, but the judgment calls made during the scan itself belong to the operator. Three stages, the mesh-to-CAD transition, reconstruction, and physical validation, contain operations that cannot be reduced to procedure without removing the expert judgment that makes them reliable. Deciding where to draw the line between these categories is the design principle of the workflow, and the next section examines where that line sits and why.

5.2.3 Tacit Knowledge and the Limits of Codification

Nonaka (1994) argues that organizational knowledge creation proceeds through a continuous conversion between explicit knowledge, which can be articulated and documented, and tacit knowledge, which is rooted in individual experience and resists full articulation. Tacit knowledge must be externalized to be shared across the organization, and explicit knowledge must be internalized to be applied reliably in practice. At Vattenfall, this conversion is currently incomplete. The reverse-engineering expertise that Respondent 8, Respondent 9, and Respondent 4 carry has not yet been externalized into documented procedure, which means it cannot be reliably transferred, scaled, or audited. This is precisely the gap that the workflow proposed in Section 5.2.2 is designed to close, not by eliminating that expertise, but by building a structure around it that makes its outputs traceable and its stages repeatable where they can be. The workflow proposed in Section 5.2.2 is designed to enable that externalization where it is possible, and to protect the knowledge that cannot be externalized without degrading it.

This distinction maps directly onto the engineering process described in Section 5.2.2. Stages 1 (component intake), 2 (preparation and setup), 4 (manual supplementation), and 7 (digital validation) can be fully codified. Receiving a green-flagged component, calibrating the scanner, measuring pre-defined features with a caliper, and overlaying a digital model on a rescanned print are operations that every competent technician should perform identically, and full specification of these stages improves rather than harms reliability. Stage 3 (scanning) sits at the middle level. Its boundary conditions, such as minimum point density and acceptable surface-coverage gaps, can be specified, but the technician's reading of the live rendering, knowing which surfaces tend to fail to capture and which areas need a second pass, depends on accumulated experience rather than on procedural instruction. At the three tacit stages identified in Section 5.2.2, the judgment calls that define the quality of the output cannot be prescribed in advance. The workflow documents that these judgments occurred and what their outputs were, but it does not attempt to prescribe how they should be made.

This pattern is the core of what this thesis calls bounded codification. The architecture of the workflow, meaning its stages, handoffs, inputs, outputs, and acceptance criteria, is fully specified. This means that anyone following the workflow knows exactly what enters each stage, what must exit it, and what the documentation must contain, even at the stages where the internal operations cannot be written down step by step. The internal operations of specific stages are deliberately left to expert judgment and named as such. A workflow exhibits bounded codification when it documents where tacit expertise is required without attempting to document how that expertise is exercised.

The practical importance of this distinction can be stated simply. If the organization tries to codify everything, it removes the personal judgment that makes the difficult stages reliable in the first place, and it produces a workflow where someone could follow every instruction perfectly and still fail. If the organization codifies too little, the workflow becomes dependent on specific individuals and cannot scale. Based on the research at Vattenfall, this second failure mode is close to how the organization operates today, with reverse-engineering work concentrated in a small number of experienced engineers and very little written down. Bounded codification threads between these two failure modes by specifying the architecture rigorously and the internal operations selectively. In plain terms: the workflow tells you what to do at every stage and what the result must look like, but at the stages where quality depends on skilled judgment, it does not pretend to tell you how to do it.

The concept extends the existing literature in two specific ways. It extends Gallivan (2001) by clarifying what routinization can look like when Nonaka's (1994) tacit content is genuinely present. Routinization occurs at the level of the workflow's architecture rather than at the level of every operation it contains. The staged pipeline becomes routine along with the handoffs between stages and the documentation produced by each stage. What does not become routine is the operational content of the stages where expert judgment is central to quality, because the workflow deliberately protects those areas. It also extends Nonaka (1994) by identifying the organizational arrangement through which tacit expertise can be embedded in a documented and reviewable workflow rather than remaining trapped in individual practice. The workflow becomes a normal and reviewable organizational activity not because every step within it has been reduced to procedure but because the organization has reached agreement on which steps need to be procedural and which need to be protected from procedure.

5.2.4 Why the Bottlenecks Are People-Problems, Not Technology-Problems

The three tacit stages of the workflow proposed in Section 5.2.2, the mesh-to-CAD bridging at Stage 5, the engineering-art reconstruction at Stage 6, and the physical validation and QC inspection at Stage 8, present themselves superficially as technical limitations of the current generation of scanning, modeling, and inspection equipment. A natural reading would suggest that better scanners, better automatic mesh-to-solid conversion algorithms, and better digital inspection tools would progressively eliminate them. The analysis developed in Sections 5.2.1 through 5.2.3 leads to the opposite conclusion. The bottlenecks are not technical in the sense that improved hardware would dissolve them. They are the empirical manifestation of operations that are constituted through expert judgment and therefore resist the kind of resolution that hardware upgrades deliver.

The mesh-to-CAD bridging is identified by the scanning expert at RISE as the workflow's principal technical bottleneck, but the substance of the bottleneck is not the polygon-to-vector conversion itself. It is the engineer's choice of which two reference points anchor the symmetry plane that the rest of the reconstruction depends on. That choice rests on judgments about which aspects of the scanned surface are reliable and which are corrupted by scanning artefacts or by the wear that motivated the reverse-engineering exercise in the first place. These choices are cases of tacit judgment in Nonaka's (1994) sense. Even if automatic mesh-to-solid tools were to improve substantially, their output would still be a geometric approximation of the scanned surface. It would not distinguish between what is wear and what was always part of the design, because that distinction is not in the scan data. It is in the engineer's understanding of how the component was originally built and how it typically degrades.

The engineering-art reconstruction at Stage 6 is the second bottleneck, and it is the one most clearly resistant to any technological resolution. Reverse engineering specialists Respondent 8 and Respondent 9's description of the work, looking for center axes, planes, and symmetries, and modeling a worn hole as round again based on how they believe it was intended, makes explicit that the judgment at stake is about design intent rather than measured reality. No scanner produces a measurement of intent. Design intent cannot be read from a scan. It has to be reconstructed from the engineer's knowledge of how this type of component was originally made, how it typically degrades, and how it fits within the system around it. A faster or higher-resolution scanner does not change the structure of this inference, because it adds more measurement to a problem whose remaining content is a matter of interpretation, not measurement.

The physical validation and QC inspection at Stage 8 is the third bottleneck, and Respondent 16 states its tacit character directly when they observes that a physical product is required before approval can be granted because reality does not always match what is on paper. Whether a weld passes, whether a balancing check reveals a fault, whether a pressure test holds: these are judgments made by an inspector reading the physical component in hand, not outputs of a digital process.

The theoretical implication is that Vattenfall's investment roadmap for AM should treat the People and Process dimensions of the PPT model as central to the remaining work, not secondary to hardware acquisition. Scanning infrastructure is in place and the reverse-engineering workflow described in Section 4.2 runs on this installed capability. Decisions about printing capacity, which technology to acquire and where to house it, remain open. What this analysis contributes to those decisions is a specific constraint: printing-capacity choices should not be made in isolation from the workflow architecture developed in Section 5.2.2, because the key bottlenecks at Stages 5, 6, and 8 will not be resolved by any particular choice of printer. This is consistent with Sjödin et al.'s (2018) finding that successful implementation in advanced manufacturing depends on coordinated attention to all three PPT dimensions. Success does not arrive through the acquisition of a more automated generation of equipment. It arrives through the organizational work of converting existing craft into a workflow whose architecture can be trusted even where its internal operations cannot be fully specified.

5.3 Digital Integration and the Conditions for Adoption

The two preceding sections have developed design proposals for component selection and reverse engineering. Both proposals assume that once a digital model exists, it can be stored, retrieved, and shared in ways that serve the organization's operational needs. This section examines that assumption. The analytical lens is Tension 3, Security versus Scalability, which captures a specific pull that emerges at the intersection of Process and People. The same security logic that governs every physical decision in a HRO must by extension govern its digital assets, yet the operational value of a digital supply chain depends on those assets being accessible, shareable, and frictionless enough to become routine. These two demands do not naturally resolve themselves, and at Vattenfall they have not yet done so. What makes this tension analytically interesting is that it cannot be resolved by tightening security routines or by relaxing them. It requires a different kind of organizational response altogether: a governance architecture that addresses not whether a given file is safe to share, but whether a growing library can be governed safely as a whole. The following sections trace how this problem has developed, why it has remained unresolved, and what that means for the conditions under which secondary adoption of AM can progress.

5.3.1 The Digital Warehouse as an Unanswered Precondition

The vision of a digital component library occupies a natural place at the end of the workflow that Sections 5.1 and 5.2 have developed. Once a component has been flagged as a candidate for AM and successfully reverse engineered into a validated CAD model, the logical next step is that the model is stored somewhere it can be retrieved, shared across sites, and eventually sent to print without the delays associated with physical procurement. Respondent 3, project leader for the AM Center initiative, describes this as the self-evident conclusion of the reverse engineering workflow: a centralized repository where a component can be identified, retrieved, and produced on demand.

What the empirical material in Section 4.3 reveals, however, is that this vision currently rests on an organizational foundation that does not exist. At the time of this study, no standardized system has been established for the secure sharing of three-dimensional models between Ringhals and Forsmark. No decision has been made regarding the architecture of a future digital component library. And, as Respondent 3 observes, the digital warehouse question is one that nobody has yet taken clear ownership of within the organization.

Holmström et al. (2010) do not treat the infrastructure question as a downstream concern to be resolved after the manufacturing capability is in place. They treat it as the condition under which the capability delivers value at all. At Vattenfall, the final link in that chain, a governed system for storing, retrieving, and sharing validated models, does not yet exist. The flag system produces a candidate component. The reverse engineering workflow produces a validated digital model. But if the infrastructure for storing and sharing that model has not been built and governed, the output of both workflows has nowhere to go. The present analysis applies the same logic: the digital warehouse is not the final step in the AM workflow. It is the precondition that determines whether the workflow produces any lasting organizational effect.

The following sections trace how that sequencing has played out in practice, beginning with the security dimension that makes the infrastructure question considerably more complex than the workflow logic alone would suggest.

5.3.2 The Aggregation Problem and the Blind Spot of Mindful Inertia

Tension 3 captures the pull between two legitimate organizational demands. The process logic of an HRO requires that digital assets be governed with the same exhaustive analysis that applies to every physical component. The people dimension of AM adoption requires that the daily digital workflow is frictionless enough to become routine, because without that frictionlessness, secondary adoption stalls before it reaches routinization.

Pettersen and Schulman (2019) describe mindful inertia as an element-by-element evaluation logic: each item entering the system is assessed individually before it is admitted. The same authors also describe the tightly coupled nature of HRO operations, where components and systems are bound together in ways where a change in one element propagates through others. Together these two features produce a blind spot that standard security evaluation logic does not account for. Mindful inertia evaluates each file individually before admitting it, but tight coupling means that the plant's components are bound together in ways that make the collection more sensitive than any single item. What is safe to share in isolation may not be safe to share at scale.

The problem emerges not from any individual decision but from the cumulative outcome of many individually approved ones. As IT-expert Respondent 20 explains, a library comprehensive enough to be operationally useful is, by the same logic, comprehensive enough to allow an outside party to reconstruct the plant's physical configuration in full. This is what makes the aggregation problem analytically significant rather than merely a practical inconvenience. It is a risk that arises between decisions rather than within them. The individual evaluation logic that mindful inertia applies, asking whether this file is safe to share, is not designed to recognize when a collection of individually safe decisions has produced a systemically dangerous outcome. That is not a deficiency of mindful inertia as a safety mechanism. It is a consequence of applying a mechanism designed for physical components to a digital context where scale changes the nature of the risk entirely.

Christianson et al. (2011) argue that HROs maintain reliability by remaining preoccupied with what could go wrong, but this preoccupation operates one decision at a time. It was never designed to ask what happens when thousands of individually safe decisions accumulate into a single collection. The evaluative logic that makes Vattenfall reliable at the component level does not automatically extend to the systemic level that a digital warehouse represents. This is not organizational negligence. It is a blind spot produced by an evaluative architecture designed for a world of physical components, where individual decisions do not combine into vulnerabilities of this kind.

The practical consequence is that Tension 3 cannot be resolved by applying existing governance logic more rigorously. It requires a qualitatively different kind of organizational decision, one that asks not whether a given file is safe to share but what governance architecture is capable of making a growing library safe as a whole. That decision has not yet been made at Vattenfall, and as the flag system and reverse engineering workflow developed in Sections 5.1 and 5.2 begin producing validated models at scale, the absence of that architecture becomes an increasingly binding constraint on the strategic value those models represent.

5.3.3 Diverging Frameworks and the Absence of Ownership

The aggregation problem identified in the preceding section has not gone unrecognized within Vattenfall. What the empirical material reveals is that the organization has not failed to see the problem but has not yet produced a clear owner of it. Understanding why requires a look at how two legitimate security frameworks have developed along separate tracks without being formally reconciled at the level where both would be visible at the same time.

LaPorte and Consolini (1991) describe the organizational immune system of an HRO as highly effective at protecting stable operations from unvalidated change introduced from within or outside a single unit. What it handles less well are risks that emerge at the boundary between organizational units, where no single function holds both the visibility and the authority to act. What the empirical material reveals is not a failure of understanding on either side, but a structural divergence between two legitimate security frameworks that have developed in different directions. Respondent 19 and Respondent 20 describe a recurring structural pattern. Ringhals operates under national security legislation and applies handling rules that are substantially stricter than Vattenfall's corporate standard. Forsmark applies an even more conservative interpretation. Centrally developed IT solutions are built to comply with the corporate classification model, and when those solutions reach the nuclear sites they frequently do not meet local requirements. As Respondent 19 describes it, the nuclear sites carry the requirement but central IT does not have access to the local management frameworks that define what nuclear requires, which means solutions are developed without the full requirement picture in view. Neither side operates irresponsibly within its own frame of reference. The problem is that the two frames have not been formally reconciled at the organizational level where both would be visible at the same time. This institutional gap has a direct bearing on the question of who owns the problem of designing a secure digital infrastructure for 3D models. Because no single function holds both the security requirement and the technical capacity to address it, responsibility for resolving the gap defaults to neither party clearly. The nuclear sites carry the requirement but rely on Vattenfall IT as a shared service for any on-premises solution. The central IT function carries the capacity but does not operate under the requirement picture that would make the gap actionable. The result is an ownership vacuum that persists not because the problem is invisible, but because the organizational structure through which it would need to be resolved does not yet exist.

This vacuum is not incidental. It is the predictable outcome of an organizational structure that, as Pettersen and Schulman (2019) note, is built to govern decisions within established units rather than to resolve conflicts between them.

5.3.4 Infrastructure as a Precondition for Secondary Adoption

The preceding sections have established that the infrastructure question is not a downstream implementation task. It is a precondition for secondary adoption to progress at all.

Primary adoption has occurred at Vattenfall. The strategic commitment to AM is established, scanning hardware is in place, and the reverse engineering workflow described in Section 5.2 is operational. What Gallivan's framework makes visible, however, is that primary adoption does not guarantee secondary adoption. The technology must become embedded in daily organizational practice before its strategic value is realized, and that embedding depends on the daily workflow being frictionless enough to reach routinization.

This is where the infrastructure question becomes analytically decisive. For the physical stages of the AM workflow, the conditions for secondary adoption are being actively built through the flag system and the reverse engineering workflow. For the digital dimension of that same workflow, those conditions do not yet exist.

Without the infrastructure to support frictionless daily use, the workflow remains at Gallivan's (2001) acceptance stage, users are committed in principle but have not integrated the technology into how they actually work. Routinization and infusion remain out of reach.

Gallivan's (2001) framework identifies routinization as the stage at which a technology becomes a normal and expected activity rather than a deliberate extra step. Routinization of the digital AM workflow requires that storing, retrieving, and sharing a validated model is as straightforward as the physical steps that produced it. That level of frictionlessness is not achievable without a prior decision about governance architecture. The decision does not need to resolve every technical detail of the system. It needs to assign ownership across the organizational gap that Section 5.3.3 identifies, establish whether the library will sit within the NSE environment shared by Ringhals and Forsmark or under a different governed arrangement, and define the handling rules that will apply to an aggregated collection rather than to individual files. Those are organizational decisions, not technical ones, and they sit within the authority of the people and functions this study has engaged.

The practical recommendation that follows is narrow but precise. The digital warehouse question should be treated as a parallel workstream to the flag system and the reverse engineering workflow, not as a downstream consequence of them. Every component that clears the seven gates and moves through the eight-stage workflow will produce a digital output that needs a governed destination. If that destination has not been decided by the time the outputs begin to arrive, the organization will have built two capable workflows that terminate in an unresolved gap. Gallivan (2001) is clear that secondary adoption stalls when the daily workflow lacks the infrastructure to become routine. The infrastructure question at Vattenfall is therefore not a matter for future research alone. It is a condition that needs to be owned, structured, and decided in organizational time, before the workflows that depend on it are operating at scale.

6. Discussion

6.1 Synthesis of Findings and Research Questions

The purpose of this study was to explore how a high-reliability organization adopts additive manufacturing in the maintenance of technically complex, long-lived industrial facilities. The study examined this through three research questions targeting tensions at the intersection of the Process, Technology, and People dimensions of the PPT framework.

RQ1 asked how component selection can be configured to identify and prioritize obsolete components for additive manufacturing. The study finds that current procurement operates reactively. This generates maintenance debt and weakens negotiating positions toward suppliers. In response, this study proposes a seven-gate flag system that redirects the organization's existing analytical caution toward the supply strategy itself. The system systematically filters candidates through legal, qualification, physical, workshop-alternative, supply and operational risk, commercial, and lead-time categories before downstream work begins.

RQ2 asked what barriers and opportunities characterize the transition from physical components to validated digital models. While 3D scanning offers clear opportunities by revealing wear patterns and geometric deviations that manual measurement misses, the reverse engineering workflow is not an automated process. It relies on tacit expert judgment at critical stages, including distinguishing operational wear from design intent, selecting reference points at the mesh to CAD transition, and conducting physical quality control. The proposed solution is an eight-stage workflow organized around bounded codification. This workflow fully specifies the architectural handoffs while deliberately protecting the stages where procedural specification would remove necessary expert judgment.

RQ3 asked how organizational structures and IT security measures affect the digital integration required for additive manufacturing. The study finds that a centralized digital component library currently lacks an organizational foundation due to three structural barriers. The first barrier is the aggregation problem, where scale creates security risks that are invisible at the individual file level. The second barrier is a structural divergence between site and corporate IT security frameworks. The third barrier is an absence of clear organizational ownership. The study concludes that secondary adoption of additive manufacturing cannot progress beyond the acceptance stage until this infrastructure gap is resolved.

6.2 Theoretical Contribution

This study makes three contributions to the literature on technology adoption in high-reliability organizations. First, the flag system shows that mindful inertia can be redirected rather than bypassed, which suggests that organizational rigidity in an HRO context does not need to be overcome for adoption to proceed. Second, the concept of bounded codification fills a gap in Gallivan's (2001) secondary adoption framework by providing a workflow design principle for contexts where tacit knowledge limits full procedural specification. Third, the study positions digital infrastructure governance as analytically prior to the adoption stages it is meant to support, extending Gallivan's framework to contexts where the enabling infrastructure is itself an unresolved organizational decision.

6.3 Practical Recommendations for Vattenfall

Four recommendations follow from the findings of this study.

First, implement the seven-gate flag system as a formal cross-functional process, as developed in Section 5.1.3. Before the system can operate reliably, component records in the internal enterprise system should be cleaned and made searchable, and the legacy contract archive should be indexed by supplier and product category, as argued in Section 5.1.4. The flag system should be communicated internally as an extension of the organization's existing reliability mandate rather than as an additional administrative layer.

Second, formally adopt the eight-stage reverse engineering workflow as the standard procedure for all components that clear the flag system. Stages 1, 2, 4, and 7 are fully codifiable and should be written as standard operating procedures and incorporated into existing quality documentation frameworks. Stages 3, 5, 6, and 8 require expert judgment and should be documented by their inputs, outputs, and acceptance criteria rather than by step-by-step instructions. The personnel who carry out the tacit stages should be formally identified, and continuity of their practice should be treated as an explicit organizational objective. Decisions about printing capacity should wait until the workflow architecture is in place, since the key bottlenecks at Stages 5, 6, and 8 will not be resolved by any particular choice of printer.

Third, assign clear organizational ownership of the digital warehouse question. As Section 5.3.4 establishes, this is not a downstream implementation task but a precondition for secondary adoption. A named owner must bridge the gap between the nuclear sites' security requirements and Vattenfall IT's delivery capacity. The architecture that best fits the constraints identified in this study is an on-premises system hosted within the NSE environment shared by Ringhals and Forsmark, governed by handling rules designed for an aggregated collection of plant files rather than for individual transfers. This decision should be made before the workflows are operating at scale, since every component that completes the eight-stage process will produce a validated digital model that needs a governed destination.

Fourth, engage proactively with the revision of the KBM and TBM qualification standards, the joint industry documents that govern material qualification at Swedish nuclear plants, to ensure that provisions for additive manufacturing are included when the update occurs. Components that pass all seven gates but cannot yet be qualified due to the absence of AM provisions in KBM and TBM should be tracked as a formal watchlist so that the organization is ready to act when the regulatory pathway opens.

6.4 Limitations

Several limitations of this study should be acknowledged.

The single-case design at Vattenfall allows for depth of analysis but limits the generalizability of the findings. The specific regulatory environment of Swedish nuclear power, including the requirements of Swedish security protection legislation, the site-specific IT governance requirements, and the KBM and TBM qualification frameworks, is not replicated in all high-reliability organizations. Researchers applying the flag system or the reverse engineering workflow to other settings should evaluate whether the gate structure and codifiability assignments remain appropriate to the local regulatory and organizational context.

The qualitative and abductive approach used in this study prioritizes the development of conceptual frameworks over precise measurement. The seven gates of the flag system and the eight stages of the reverse engineering workflow are derived from interview material and document analysis. They have not been tested against a full implementation cycle, and the conditions under which each gate and each stage functions as intended remain to be empirically verified.

RQ3 is addressed at the diagnostic level. The three structural barriers identified, the aggregation problem, the divergence of security frameworks, and the absence of ownership, describe why a governed digital library does not yet exist rather than specifying how one should be built. The architectural question of what a functional on-premises digital warehouse for 3D models would look like, including its access controls, audit mechanisms, and inter-site transfer protocols, is beyond the scope of this study and requires dedicated further work.

The analysis in Section 5.3 rests primarily on two respondents with information security expertise. While their accounts are consistent with each other and with the broader organizational picture, the findings about the aggregation problem and the governance gap would benefit from triangulation against additional sources, including perspectives from central IT functions that were not directly represented in the interview sample.

Finally, the interview sample, while broad in functional coverage, is concentrated within two nuclear sites and supplemented by a small number of external industry partners. Perspectives from nuclear operators in other countries that have progressed further in AM adoption could have enriched the comparative basis for the findings and strengthened the transferability of the proposed frameworks.

6.5 Future Research

Three directions for future research emerge from this study.

The most immediate is an evaluation study following the implementation of the flag system and the reverse engineering workflow at Vattenfall. Such a study could test whether the gate sequence and the codifiability assignments proposed here hold in practice, identify where the organizational bottlenecks are most severe, and document the adjustments that the implementation process requires.

A second direction is a comparative study of nuclear operators that have moved further along the AM adoption curve, particularly in France where established industry partnerships already exist. Comparing how different regulatory environments and organizational structures have shaped workflows, qualification processes, and digital infrastructure decisions in those settings would allow the concepts of bounded codification and redirected mindful inertia to be tested against a broader empirical base.

A third direction concerns the governance architecture of the digital component library. This study identifies the need for an on-premises, NSE-hosted solution governed by handling rules designed for aggregated collections, but it does not specify how such a system should be designed or audited. Future research combining information security, organizational theory, and nuclear regulatory expertise would be required to develop that specification.

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