DOCTORAL THESIS

Still in the Loop

Understanding Operator Work in Autonomous Mining Systems

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dann erschallet des Bergmannes Gruß bei der Nacht,
Glück auf, Glück auf, Glück auf, Glück auf

der Steiger kommt

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The journey towards a doctoral degree is much like Bilbo's journey in Tolkien's *The Hobbit* – it begins as an adventure, full of curiosity and excitement, but soon turns into a path marked by hardship, uncertainty, and unexpected turns. Yet, just like Bilbo, I have not travelled alone. Along the way, I have been accompanied, supported, and encouraged by many others. I would therefore like to take a moment to acknowledge those who have been especially important to me during this journey – seeing me *there and back again.*

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Luleå, November 2025
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Summary

As autonomous technology becomes more deeply embedded in industrial production, the boundaries between human and machine are being redrawn, giving rise to new uncertainties about the meaning of work and the conditions under which work is carried out. In mining, where production systems are complex, interdependent, and capital-intensive, technical innovation is often driven by promises of greater efficiency and safety. At the same time, these ambitions often risk overshadowing social and organisational concerns. The industry's development of highly automated and data-driven systems has tended to privilege technical performance, leaving questions of human involvement, competence, and responsibility underexamined. When technologies are designed to minimise human intervention but continue to depend on human judgement, a paradox arises: work is reconfigured rather than removed, and the success of the system ultimately rests on those it seeks to replace.

Against this background, the thesis explores how autonomous mining systems are designed, developed, and implemented, and how these processes reshape the work of operators. Its aim is to understand the implications of autonomous systems for operator work by analysing the underlying design and development logics and the organisational changes that follow their implementation. In doing so, the research seeks to illuminate how technological ambitions meet workplace realities and how human and technical subsystems become intertwined in practice.

The analysis combines two complementary perspectives that together bridge the technical and social dimensions of technological change. *Sociotechnical Systems Theory* provides a foundation for understanding how technical and social subsystems interact and how their balance is crucial for safe and sustainable forms of work. The theory of *Communities of Practice* extends this view by highlighting implementation as a social process through which people negotiate meaning, build competence, and make new technologies workable in practice. In combination, these perspectives make it possible to analyse autonomous mining systems as sociotechnical phenomena, highlighting their implications for how design logics, organisational structures, and everyday work intersect.

Empirically, the thesis builds on three interrelated qualitative studies that together trace the trajectory from the design and development of autonomous systems to their implementation in mining practice. The studies include a review of existing research on digital transformation in mining, a focus group study with technology developers, and an in-depth case study of an autonomous haulage system in Sweden. Taken together, they provide complementary insights into how assumptions embedded in design are negotiated, adapted, and made workable in organisational settings, revealing how technological ambitions are redefined through everyday practice.

Across the studies, the thesis reveals a tension between the intentions guiding design and the realities of implementation. While development processes frame operators as peripheral to system performance, implementation reintroduces them as central actors in making technology function in practice. The everyday work of sustaining production continues to rely on human judgement, coordination, and anticipation, even as these tasks become more analytical and distributed across roles. Rather than being displaced, operators remain "still in the loop", though in transformed ways that demand new forms of attention, collaboration, and responsibility.

The findings point to a complex reality where autonomous systems reconfigure rather than replace human work, creating new interdependencies between people, technology, and organisation. These developments have implications for how work is organised and understood, influencing the distribution of competence, collaboration, and control across human and technical domains. In this sense, autonomous technology emerges not only as a technical transformation but as a reorganisation of the conditions under which work is carried out and experienced.

In conclusion, the thesis offers insights into how human and technological systems evolve together within contemporary mining. By bringing sociotechnical and practice-based perspectives into dialogue, it highlights how autonomous technology unfolds as an ongoing process of negotiation and adaptation, rather than a fixed outcome of design and development. This perspective deepens understanding of how work is continually rebalanced between people and technology, and how such rebalancing shapes both organisational life and the experience of work. The future of technological development in autonomous mining systems, this thesis suggests, lies not in separating human and machine, but in understanding how their interaction can sustain safer, more adaptive, and more meaningful forms of work.

Sammanfattning

När autonoma teknologier blir alltmer integrerade i industriproduktionen förändras gränserna mellan människa och maskin, vilket väcker nya frågor om arbetets innebörd och de villkor under vilka arbetet utförs. Inom gruvindustrin, där produktionssystemen är komplexa, ömsesidigt beroende och kapitalintensiva, drivs den tekniska utvecklingen ofta av löften om ökad effektivitet och säkerhet. Samtidigt riskerar dessa ambitioner att skymma sociala och organisatoriska aspekter av arbetet. Utvecklingen av alltmer automatiserade och datadrivna system har tenderat att prioritera teknisk prestanda, medan frågor om mänsklig delaktighet, kompetens och ansvar till stor del har förblivit outforskade. När tekniken utformas för att minimera den mänskliga inblandningen men fortfarande är beroende av mänskligt omdöme uppstår en paradox: arbetet omformas snarare än försvinner, och systemets framgång vilar ytterst på dem som det är tänkt att ersätta.

Mot denna bakgrund undersöker denna avhandling hur autonoma gruvsystem utformas, utvecklas och implementeras, och hur dessa processer förändrar operatörernas arbete. Syftet är att förstå vad införandet av autonoma system innebär för operatörsarbetet genom att analysera de design- och utvecklingslogiker som präglar tekniken och de organisatoriska förändringar som följer när den tas i bruk. Studien belyser därigenom hur tekniska ambitioner möter arbetslivets realiteter och hur mänskliga och tekniska delsystem sammanflätas i praktiken.

Analysen bygger på två kompletterande teoretiska perspektiv som tillsammans förenar de tekniska och sociala dimensionerna av teknologisk förändring. *Socioteknisk systemteori* ger en grund för att förstå samspelet mellan tekniska och sociala delsystem och hur balansen mellan dem är avgörande för säkra och hållbara former av arbete. Teorin om *praktikgemenskaper* fördjupar denna förståelse genom att lyfta fram implementering som en social process där människor förhandlar mening, utvecklar kompetens och får den nya tekniken att fungera i praktiken. Tillsammans möjliggör dessa perspektiv en analys av autonoma gruvsystem som sociotekniska fenomen, där teknikens implikationer för designlogiker, organisationsstrukturer och

vardagsarbete står i centrum.

Empiriskt bygger avhandlingen på tre sammanlänkade kvalitativa studier som tillsammans följer den autonoma teknikens väg från utveckling till praktisk användning i gruvmiljöer. Materialet omfattar en litteraturöversikt över forskning om digitalisering i gruvindustrin, en fokusgruppsstudie med teknikutvecklare samt en fallstudie av ett autonomt transportsystem vid en svensk gruva. Tillsammans ger dessa studier kompletterande inblickar i hur de antaganden som präglar designen förhandlas, anpassas och görs fungerande i organisatorisk praktik – och hur teknologiska visioner omformas i mötet med vardagens arbete.

Genom studierna synliggörs en spänning mellan de intentioner som präglar design och de realiteter som uppstår vid implementering. Utvecklingsprocesser tenderar att framställa operatörer som perifera i förhållande till systemets funktion, medan implementeringsfasen åter gör dem centrala för att tekniken ska fungera i praktiken. Det dagliga arbetet med att upprätthålla produktionen vilar fortsatt på mänskligt omdöme, koordinering och framförhållning, även om dessa uppgifter blir mer analytiska och fördelade över olika roller. Operatörerna försvinner inte ur systemet, utan förblir – om än i förändrad form – avgörande för att produktionen ska fungera och hållas samman i praktiken.

Avhandlingens resultat pekar på en komplex verklighet där autonoma system omformar snarare än ersätter mänskligt arbete, och där nya ömsesidiga beroenden uppstår mellan människor, teknik och organisation. Dessa förändringar har betydelse för hur arbete organiseras och förstås, och påverkar fördelningen av kompetens, samarbete och kontroll mellan mänskliga och tekniska områden. I detta perspektiv framträder autonom teknik inte bara som en teknisk förändring, utan som en omstrukturering av de villkor under vilka arbete både utförs och upplevs.

Avslutningsvis bidrar avhandlingen med en fördjupad förståelse av hur mänskliga och tekniska system utvecklas tillsammans inom den samtida gruvindustrin. Genom att förena sociotekniska och praktikbaserade perspektiv visar den hur autonom teknik tar form som en pågående process av förhandling och anpassning, snarare än ett fastställt resultat av design och utveckling. Denna förståelse fördjupar insikten om hur arbete ständigt omfördelas mellan människor och teknik, och hur denna balans påverkar både organisation och arbetslivets innehåll. Avhandlingen pekar mot att framtidens teknikutveckling för autonoma system till gruvindustrin inte handlar om att skilja människa och maskin åt, utan om att förstå hur deras samspel kan bidra till säkrare, mer flexibla och meningsfulla former av arbete.

List of Appended Papers

I Lund, E., Pekkari, A., Johansson, J., & Lööw, J. (2024). Mining 4.0 and its effects on work environment, competence, organisation and society – a scoping review. *Mineral Economics, 37*, 827-840. https://doi.org/10.1007/s13563-024-00427-0

II Lund, E., Johansson, J., & Lööw, J. (2024). The Designers' Perspective on Autonomous Mining Systems and Sociotechnology. *Mining, Metallurgy & Exploration, 41,*, 647-657. https://doi.org/10.1007/s42461-024-00952-0

III Lund, E., & Nygren, M. (N.D). With One Foot in The Future – Situating Autonomous Systems in Mining through Communities of Practice. *Unpublished manuscript:* SUBMITTED TO: *Journal of Organizational Change Management,* September 2025.

IV Lund, E. (N.D). Autonomy for whom? Implications of Cyber-Physical Mining Systems for Operator Work and Organisation. *Unpublished manuscript:* SUBMITTED TO: *Applied Ergonomics*, November 2024.

List of Abbreviations

AHS	Autonomous Haulage System
AI	Artificial Intelligence
GMG	Global Mining Guideline group
LOA	Level of Automation
OEM	Original Equipment Manufacturer
PEO	Population, Exposure, Outcome
R&D	Research and Design

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1 Introduction

"There is nothing like looking, if you want to find something."
– *J.R.R. Tolkien,* The Hobbit

The design and development of autonomous mining systems unfold as a complex and fragmented process, involving multiple actors and guided by technically oriented logics that unintentionally marginalise operators as well as social and human perspectives. Yet implementation represents a moment of rebalancing, where negotiation, meaning-making, and social dynamics continually reshape both technology and work.

This thesis explores how autonomous mining systems are changing the work of operators. It focuses on the design, development, and implementation of these technologies, and how they reshape the everyday work of operators. In mining, issues of work and work environment have long been central to research and policy due to the industry's demanding physical conditions and high safety requirements (Abrahamsson & Johansson, 2006; Abrahamsson, Johansson, & Johansson, 2009; B. Johansson, Johansson, & Abrahamsson, 2010). As autonomous technologies and digitalisation accelerate, these concerns increasingly extend beyond physical conditions to include psychosocial and organisational aspects of work (Lööw, 2020a, 2020b). The psychosocial work environment has long been recognised as crucial for health and wellbeing, where factors such as influence, participation, and control in one's work, as well as leadership, power relations, group dynamics, and stress, play an important role (Thylefors, 2019). Similarly, research on production and work organisation highlights the importance of the organisational context and the vision of creating good and sustainable forms of work through reasonable rationalisation – emphasising self-managed planning levels, continuous learning, integrated maintenance, and systematic environmental efforts (J. Johansson & Abrahamsson, 2019). In parallel, perspectives from human–machine systems research stress that effective and safe work increasingly depends on the interplay between human and technical subsystems, including processes of attention, perception, decision-making, problem-solving, and supervisory control (Osvalder & Ulfvengren, 2019).

These developments also intersect broader societal trends. Across much of the Western world, manufacturing and heavy industry have declined or moved to low-cost regions, raising concerns about deindustrialisation and economic dependency (Liboreiro, Fernández, & García, 2021). At the same time, industries that remain often struggle to attract and retain skilled labour, particularly in demanding environments such as mining (B. Johansson & Johansson, 2014; J. Johansson, Johansson, Lööw, Nygren, & Abrahamsson, 2018; J. Johansson & Abrahamsson, 2009; Lööw, Johansson, Andersson, & Johansson, 2018; Lööw, 2020a). Against this backdrop, autonomous technologies and Artificial Intelligence (AI) are frequently presented as part of the solution: a means of maintaining productivity, addressing labour shortages, and revitalising industrial competitiveness (Lund, Pekkari, Johansson, & Lööw, 2024; Long, Schafrik, Kolapo, Agioutantis, & Sottile, 2024).

Related to this, research on digitalisation in the Nordic countries shows a different picture. Rather than productivity gains and large-scale job loss, digital technologies have, as of yet, primarily reshaped how work is organised and what skills are required (Rolandsson & Dølvik, 2021). Studies of the work environment similarly indicate mixed outcomes, where digitalisation can create new forms of work, whilst also contributing to higher demands, increased stress, and growing organisational control (Palm & Rosengren, 2020). These developments tend to benefit high-skilled and knowledge-intensive occupations, whereas labour-intensive sectors are more likely to experience strain and fragmentation.

Technological change is also not without ethical implications for work and organisational life. As autonomous technology becomes increasingly paired with AI, questions arise about responsibility, agency, and the human experience of working with intelligent systems (Fischer & Frennert, 2025). From this perspective, the development and implementation of autonomous mining systems bring ethical and organisational questions to the forefront of everyday work, influencing how responsibility, competence, and decision-making are negotiated in practice.

In mining, these questions take on a particularly tangible form. Autonomous systems are increasingly used in mining operations for tasks such as transporting materials, drilling and blasting, both in underground and open-pit operations (Global Mining Guideline Group, 2024). One of the central issues with autonomous systems in mining is that they are not really autonomous. In practice, their operation depends on continuous human involvement – before, during, and after deployment. Therefore, there is a paradox inherent in the ambition of these systems: they are intended to reduce or eliminate the need for human operators; that is, if the technology really were autonomous, then operator involvement would be eliminated. Yet, the success of many autonomous systems relies heavily on human judgement, adaptation, skill, and knowledge. This issue was first articulated by Bainbridge (1983), who described the *Ironies of Automation*: that attempts to eliminate human error using automation technologies often create new problems or leave operators responsible for tasks that are difficult to automate. The reshaping – rather than removal – of operators presents a critical problem because it creates uncertainty about what skills operators need to possess, increases cognitive demands on workers managing increasingly complex technical systems, and may lead to imbalance or oscillation between automation technologies and human intervention, potentially undermining safety, efficiency, and worker satisfaction (e.g. Woods & Sarter, 1998; Bainbridge, 1983).

This challenge is particularly acute for the mining industry, where operations take place in harsh environments and often involve high risk in tightly coupled production systems. Mining processes are complex and interdependent, requiring careful integration between human operators and technical solutions. As autonomous technology advances, this interdependence does not diminish but rather takes new forms, demanding new skills and knowledge among operators (Chirgwin, 2021).

In this context, poor integration of autonomous technology risks generating significant consequences – operationally, through disruptions and technical malfunctions, and socially, through stress, frustration, and challenges to the work environment (Pascoe, 2020; Burgess-Limerick, 2025). These issues are becoming increasingly salient as the mining industry expands its use of autonomous technologies, ranging from haul trucks to emerging applications of AI and machine learning in production systems (Scott, 2022; Global Mining Guideline Group, 2024).

There is therefore a pressing need to better understand how autonomous mining systems are designed, developed, and implemented, and how these processes reshape operator roles, skills, and practices. Such understanding cannot eliminate uncertainty – these systems will always display emergent properties – but it is essential for anticipating potential tensions, aligning expectations, and supporting more effective interaction between operators and autonomous systems.

At the same time, these systems reveal a central paradox. While designed to operate autonomously, they remain dependent on human judgement, adaptation, and intervention – dependencies that become most visible in moments of disturbance. As Bainbridge (1983) observed, automation can paradoxically increase rather than reduce demands on operators. When removed from direct control but expected to intervene when failures occur, operators may lack the situational awareness or practical experience needed to respond effectively (e.g. Woods & Sarter, 1998). Such conditions risk turning operators into passive monitors whose work is defined by system performance rather than professional competence or discretion (Bainbridge, 1983). Over time, this may lead to task fragmentation, loss of engagement, and new forms of dependency. Furthermore, the uneven distribution of these effects may create or reinforce divisions between occupational groups: while some operators gain opportunities to develop new competences and collaborate with technology developers, others become marginalised or excluded from such processes (Abrahamsson & Johansson, 2006).

Research on automation and work in other industrial domains has shown that the introduction of new technologies rarely replaces human labour directly. Instead, it typically leads to a reconfiguration of work tasks, competences, and organisational responsibilities. For instance, recent studies have examined how collaborative automation strategies are reshaping production environments (Fast-Berglund, Salunkhe, & Åkerman, 2020), and how human interaction is informed by cognitive ergonomics and human factors (Thorvald, Fast Berglund, & Romero, 2021; Gualtieri, Fraboni, A. Billing, Thorvald, & Helen Rosen, 2025). These contributions highlight that technological systems are not only shaped by technical design but also by organisational arrangements, human skills, and workplace cultures – insights that are equally relevant for understanding similar dynamics in mining.

In mining research, studies of operator–technology interactions have largely emerged within engineering. This body of work has generated valuable knowledge about safety, risk management, physical working conditions, and system integration (e.g. Lynas & Horberry, 2011; Burgess-Limerick, 2025; Sundström, 2025). However, this focus on technical and ergonomic interfaces has tended to leave aside social and organisational processes through which autonomous systems are developed and made workable in practice. Meanwhile, research adopting social or organisational perspectives has addressed mining technology more broadly, without examining the specific challenges introduced by autonomous technology (e.g. Lööw, 2020b). As a result, there remains limited understanding of how autonomous mining systems are shaped and reshaped through the intertwined processes of design, development, and implementation. Examining these dynamics offers a way to understand how technological change materialises in everyday work – not as a fixed outcome, but as an ongoing organisational and social accomplishment.

Beyond industrial settings, research on automation in the public sector has provided complementary insights into how technology reconfigures work and professional responsibility. Studies of robotic process automation and algorithmic decision-making have shown how systems can challenge established norms, discretion, and professional identities (Ranerup & Svensson, 2023, 2024; Germundsson, 2025). Although such developments concern digital rather than physical automation, they underline that the social and ethical dimensions of automation are inseparable from implementation processes, even for highly technical contexts such as mining.

While research in other domains has highlighted the social dimensions of automation, this thesis turns to the mining industry to explore how questions of work and human involvement emerge through the design, development, and implementation of autonomous systems. The mining sector provides a particularly revealing context, where technological innovations are often seen as a universal solution to virtually all challenges (Lööw, 2020b). As Lööw argues, such expectations risk obscuring the social and organisational dimensions of work, which remain critical in an industry characterised by complexity, interdependence, and risk.

The thesis examines how autonomous systems and operator roles are mutually reshaped across design, development, and implementation. It shows how assumptions embedded in the design and development of autonomous systems are negotiated and adapted as technologies are integrated into organisational practice. Conceptually and empirically, the thesis contributes to a more integrated understanding of autonomous systems in mining – one that emphasises how technological systems are not simply introduced into existing settings but made workable through continuous human adaptation and negotiation.

By analysing these processes in depth, the thesis sheds light on how operator work is reshaped and how human capabilities and technological systems are mutually constituted in complex industrial environments. This perspective provides a more empirically grounded understanding of how technological ambitions meet workplace realities, and their implications for the future of industrial work.

1.1 Purpose and Research Questions

The purpose of this thesis is to explore and better understand the implications of autonomous systems for operator work in the mining industry by examining both the underlying design and development logics and their implementation. To explore these issues systematically, the following research questions have been formulated:

(i) *What underlying assumptions, logics, and priorities guide the design and development of autonomous mining systems?*

(ii) *How does the implementation of autonomous mining systems reshape operator roles, practices, and organisational dynamics?*

1.2 Clarifications

Several key terms used in these questions require clarification. By design logics, I refer to the underlying assumptions, priorities, and rationalities that orient the development of autonomous systems in mining, shaping what is considered relevant or legitimate in design practice, particularly in relation to work and its organisation.

The term autonomous mining systems is used here in a preliminary sense to denote technologies that are labelled or treated as autonomous in mining, even though their functioning in practice always relies on human involvement. A more detailed discussion of what constitutes such systems, and how they are understood in this thesis, is provided in a later part of the thesis (Section 3.1.3).

Operator roles and practices are understood broadly, encompassing not only formal job descriptions but also competences, interactions, and identities through which operators carry out their work. This broader understanding recognises that roles are not fixed or predefined, but enacted through practice and are continuously negotiated as they evolve.

Organisational dynamics refers to the evolving patterns of roles, responsibilities, coordination, and decision-making within mining organisations as autonomous systems are developed and implemented. Finally, implementation is used here in a broad sense, not merely as the technical rollout of a system but as the process through which new technologies are negotiated, adapted, and made workable in practice. As later chapters will show, the empirical analysis also demonstrates how implementation takes shape as a process of rebalancing between technical priorities and social concerns.

1.3 Overview and Structure

The thesis is based on qualitative data from three interrelated studies. First, a scoping literature review study was conducted to map existing knowledge about *Mining 4.0*[1] in mining contexts – and its effects on work, competence, organisation, and society, helping to identify relevant themes and research

[1] The term "Mining 4.0" extends the concept of "Industrie 4.0" (Kagermann, Wahlster, & Helbig, 2013) to the context of mining; cf. Bongaerts (2020).

gaps.[2] Second, a focus group study involving technology designers and developers was carried out to explore the assumptions about operators and operator–technology interaction that inform the early stages of autonomous system design. Third, an in-depth case study was conducted to investigate the implementation of an autonomous haulage system in the Swedish mining industry. Data collection for this study took place at a large mining company undergoing a transition towards an autonomous haulage system. In addition, field notes were collected throughout the research process to support the analysis and overall understanding presented in this thesis.

This thesis is structured in six chapters. Chapter 2 provides the contextual foundation by outlining the characteristics of the mining industry, from the European to the Swedish context, and the collaborative arrangements that shape the development of autonomous systems. Chapter 3 clarifies terminology and introduces the theoretical foundation, including perspectives from automation research, *Sociotechnical Systems theory*, and *Communities of Practice*. Chapter 4 presents the methodology and empirical foundation of the thesis, describing the studies conducted and the scientific process that guided their design and execution. Chapter 5 summarises the four appended papers, each of which contributes to understanding different phases of design, development, and implementation, and their implications for operator work. Chapter 6 synthesises the analytical findings in relation to the research questions, discusses theoretical contributions, analytical insights, and practical and societal implications, offers directions for future research, and ends with concluding reflections.

[2] The concept of "Industry 5.0" has emerged as a policy and research framework during the process of working with this thesis, emphasising sustainability, resilience, and human-centric values in production systems (European Commission, 2021). While discussions of "Mining 5.0" are beginning to appear, the term was not established in the mining literature at the time the review was conducted. For consistency, this thesis therefore uses the term "Mining 4.0".

2 Contextual Foundation

The purpose of this chapter is to situate the thesis within the industrial and organisational context in which autonomous mining systems are developed and implemented. Rather than providing a comprehensive history or overview, the chapter outlines key characteristics of the mining industry that influence how the development of autonomous mining systems takes shape in practice. It describes the technological conditions of mining, variability across sites, capital investment patterns, workforce structure, and collaborative arrangements between mining companies, original equipment manufacturers (OEMs), and other actors. Together, these elements form the backdrop for the empirical and analytical focus on operator work that follows in later chapters.

The development and implementation of autonomous systems in mining involves a wide range of stakeholders. In this thesis, the term “stakeholder” refers primarily to the actors who participate in or are affected by the design, development, integration, and use of autonomous technologies in mining contexts. These include mining companies, who not only implement and use autonomous systems but also participate in their design and integration; OEMs and technology developers, who shape technologies as designers and suppliers while collaborating with industry partners; and control-room and machine operators, who remain central stakeholders as their work practices are directly transformed by these systems. Industry networks and policy actors also constitute part of the broader context in which priorities and guidelines for the mining sector are developed, but they are not examined directly in this thesis. Parts of the material for this chapter are drawn from research collaborations and fieldwork that engage with several of these groups.

2.1 Mining Industry Characteristics

Historical Evolution of Mining Technology

From a historical perspective, the mining industry has undergone significant technological transformation during the past century (Coulson, 2012), though not uniformly across all contexts or regions. The trajectory of change differs between mine types, ownership models, and national settings. However, among large-scale industrial mining operations – particularly in countries like Sweden, Canada, and Australia – one can observe a shift from labour-intensive manual practices to increasingly mechanised and large-scale production systems (Eriksson, 1991; Abrahamsson & Johansson, 2006), and more recently, autonomous systems (Lund, Pekkari, et al., 2024; Lund, Johansson, & Lööw, 2024).

The first major technological shift began with mechanisation in the early and mid-20th century, when machinery such as engines, drills, haul trucks, pumps, and conveyor belts began to replace manual labour (Abrahamsson & Johansson, 2006). This development significantly increased operational efficiency and marked a departure from traditional forms of physically demanding work. Compared to previous industrial revolutions, the mechanisation of mining had a particularly profound impact on underground environments, where mobility, ventilation, and human endurance had previously constrained production. In these constrained environments, machines became necessary extensions of the body, and their integration transformed not only productivity but also work organisation, skill requirements, and safety conditions. The historical development of mining technology in Sweden is well documented in J. Johansson's study of LKAB and further elaborated in Abrahamsson and Johansson (2006). The latter traces the evolution from early mechanisation in the 1950s to the gradual introduction of automation in Swedish iron ore mining in the early 2000s. The article highlights how new technologies did not simply replace old ones, but were gradually layered into existing systems, reshaping the distribution of skills, responsibilities, and spatial arrangements underground.

Automation followed mechanisation and introduced control systems that allowed certain processes to run automatically, while others remained semi-automatic or tele-remote (Abrahamsson & Johansson, 2006; Darling, 2011a; Randolph, 2011). However, automation was not introduced evenly across the mining process. It was initially implemented in the later stages – such as mineral processing and refining – where environmental conditions are relatively stable and predictable. These downstream processes are typically housed in fixed surface facilities with permanent infrastructure and predictable flows, making them far easier to automate. In contrast, the earlier stages of mining – that is, extraction – involve breaking and transporting material within an underground or open-pit environment. These environments are geologically dynamic, spatially shifting, and continuously reshaped by production. Unlike processing plants, extraction requires systems that can *follow the mountain*, the ore body, as it moves or becomes less accessible. These conditions delayed the implementation of automation in extraction, as technology was not yet mature enough to manage this complexity, variation, and safety risks involved. In the late 20th century and early 21st century, computer-based systems and semi-autonomous equipment – such as drills, loaders, and haul trucks – were beginning to be introduced into mining operations, enabling more sophisticated forms of control and coordination (Darling, 2011a; Randolph, 2011).

Building on these developments, the industry has in recent years entered a phase marked by the development of autonomous mining systems. These systems go beyond automating isolated tasks and instead aim to coordinate multiple machines and subsystems as part of integrated production flows. They are now being tested and implemented in various parts of the mining process – including extraction and transportation (Lund, Pekkari, et al., 2024; Lund, Johansson, & Lööw, 2024; Pascoe, 2020; Global Mining Guideline Group, 2024). While global adoption of autonomous systems still remains limited to specific applications and settings, the direction is clear: research and development efforts continue to expand the role of autonomous mining systems.

This thesis focuses specifically on the domain of extraction – the part of mining where technological innovation related to autonomous technology is currently advancing most rapidly. As automation technologies have matured and new systems have become available, extraction has emerged as a key site for development and implementation. It is in this domain that new roles, practices, and tensions surrounding autonomous systems are most actively being negotiated – and it is here that this thesis has its empirical and analytical focus.

Technological Diversity and Variability

This section addresses how mining technology varies between contexts due to geological, organisational, and technological factors.

No two mines are alike. Each ore body differs in shape, composition, depth, and location, and these characteristics dictate which extraction methods are most suitable (Nelson, 2011). As indicated above, extraction must follow the mountain, adapting to its unique geological and environmental conditions. This leads to a broad variety of mining methods for both open-pit mining and underground mining, such as block caving, room-and-pillar, sublevel caving, cut and fill (overhand and underhand), longwall mining, etc. (Carter, 2011). The choice of method depends not only on the type of material being extracted, but also on its physical and chemical properties, ore geometry including depth, and surrounding rock conditions. Some mining operations even employ multiple methods within the same site, combining techniques to accommodate complex or heterogeneous ore bodies.

This thesis focuses on large-scale, industrial mining operations, and does not address artisanal and small-scale mining, which operate under different conditions and typically do not involve autonomous technologies. By "large-scale, industrial mining operations", this thesis refers to capital-intensive, high-volume production environments typically operated by medium to large companies under formal regulatory and technological infrastructures. These operations differ markedly from artisanal and small-scale mining, which often take place in informal economies, involve minimal mechanisation, and are shaped by fundamentally different social, economic, and technical conditions (Hilson, 2002). Artisanal and small-scale sites generally lack the capacity for autonomous technology, and fall outside the scope of this study.

Technologies that work well in one mine may be impractical or inefficient in another. Even when similar equipment is used across different sites, its configuration, integration, and operation may differ (Darling, 2011b). These differences extend not only between mining regions, but also between companies operating under similar conditions, reflecting organisational preferences, legacy systems, and varying levels of technological maturity. Even within large-scale mining operations, this inherent variability means that technological solutions are highly context-dependent. For instance, autonomous haulage systems might be viable in a wide open-pit iron ore mines, but prove inefficient in a narrow-vein underground mines. The same applies to communication systems – underground operations may require advanced wireless mesh networks, while surface operations can use simpler satellite or cellular systems.

Differences in technological solutions can also reflect broader organisational and structural conditions, such as ownership models and the financial and strategic resources available for technological investment. While privately owned mines may have different incentives and investment logics than state-owned ones, such distinctions do not always lead to predictable patterns. In the Swedish context, for example, the state-owned company LKAB is sometimes perceived as more conservative in its approach to new technologies, yet historical and anecdotal observations suggest that this can vary significantly over time depending on managerial priorities and leadership.[3] These dimensions, while beyond the empirical scope of this thesis, may further contribute to explaining variation in the adoption and configuration of autonomous systems in mining.

The diversity of mining environments complicates the development of one-size-fits-all solutions for autonomous mining systems and limits the transferability of practices between contexts. However, while mine sites differ significantly, there are still many underlying structural similarities – particularly in the types of tasks that need to be performed and the broad categories of equipment used. As a result, similar technological solutions are often applied across sites, albeit with modifications to account for local conditions. Rather than uniform replication, implementation typically involves adaptation, calibration, and integration into specific systems. This requirement influences how equipment is designed: technologies must be, to some extent modular, configurable, or flexible enough to accommodate different mining operations. These underlying structural similarities include the sequence of key mining tasks: drilling, blasting, scaling, loading, and hauling material to mineral processing sites (Darling, 2011b). Although the equipment and scale may vary, the fundamental operations of fragmenting rock and removing broken material follow a consistent logic across mine types. Similarly, the types of equipment used – such as haul trucks, loaders, and drills – often fall within standardised categories, even if their specifications differ.

In addition, the need for local adaptation is reinforced by the dynamic nature of mining production systems. Unlike fixed industrial environments such as automotive factories, where the layout and flow of production can remain fairly stable over time, mining operations must continuously evolve in response to the shifting conditions of the ore body. As mining progresses, infrastructure, equipment, and work practices must be adjusted accordingly (Lööw & Nygren, 2019). This continual reshaping places additional demands on the flexibility of technological systems and further complicates attempts to standardise or replicate solutions across sites.

While adaptability and interoperability are often stated goals in the design of mining technologies, the pace of technological change in mining is generally slow relative to mines' long investment cycles. Consequently, even when equipment and software are regularly updated, new systems are typically layered onto legacy infrastructures, which constrains flexibility from the outset. Vendor dependence, integration hurdles, and extensive site-specific customisations further reduce the ability to redeploy or reconfigure technologies across settings, while knowledge and control over critical

[3] Documented as part of a broader set of field notes compiled during the research process (see also Section 4.2.4).

systems often shift to external suppliers (Olsson & Franke, 2019). Some companies deliberately externalise technological ownership and rely heavily on vendors, whereas others aim to retain control and develop or own key solutions themselves. In both cases, however, mining companies must live with technological choices that often entail compromises and after-the-fact adjustments to make systems workable in practice.

While this section focuses on technological and organisational variability at the site and company level, national differences – such as regulatory regimes, labour relations, or policy support for automation – may also shape how mining technologies evolve and are implemented. These aspects are not discussed here, but are addressed in relation to the Swedish context later in the chapter. Asymmetries in technological maturity are not limited to individual sites or companies; they also appear at the national level (Eurostat, 2022). Regulatory frameworks, public investment strategies, digital infrastructure, and workforce competence all shape the pace and direction of automation. These national and international asymmetries provide an important backdrop for understanding how and why mining technologies evolve.

Capital Intensity and Technological Conservatism

A defining characteristic of the mining industry is its high capital intensity (Crowson, 2011). Establishing and operating a mine requires substantial long-term investments in equipment, infrastructure, and site development. Because these costs are considerable and largely fixed, mining companies engage in long-term financial planning and tend to prioritise stability and risk mitigation.

These economic conditions contribute to a technological conservatism within the industry. The high costs and operational complexity associated with implementing new technologies make companies cautious. Innovations are often introduced incrementally rather than disruptively, with a strong preference for proven, reliable solutions (Bäckblom et al., 2010). Once a particular system or supplier has been selected, it tends to shape subsequent technological decisions, creating path dependencies and making alternatives less feasible – a form of technological lock-in. Over time, these embedded choices may have unintended consequences for work and organisation. When investments are made without fully anticipating their long-term implications for labour practices, operational flexibility, or system adaptability, the result can be a misalignment between technology and the evolving demands of the workplace. In this way, the industry's long investment horizons and aversion to disruption can make it not only financially but also socially, conservative.

Global and Economic Context

The mining industry operates on a global scale, with commodity prices largely determined on international markets.[4] Most mining companies have limited influence over the prices of the materials they extract, as these are typically set through global trading platforms or long-term contracts. For many base and precious metals – including copper, gold, and zinc – prices are set on the *London Metal Exchange*, one of the world's leading commodity exchanges, and the *New York Mercantile Exchange* (Humphreys, 2011). In contrast, iron ore is not traded on the London Metal Exchange but is priced through a combination of spot markets, index pricing, and long-term contracts, often negotiated bilaterally between major producers and buyers. While a few dominant producers – such as BHP, Rio Tinto, and Vale – can influence supply expectations due to their market share, individual firms generally do not control pricing.[5]

As a result, mining companies primarily compete by reducing production costs and increasing operational efficiency. This focus is driven by the global nature of commodity markets, where individual producers have limited influence over market prices. Since minerals are traded on international exchanges with high price volatility, companies cannot easily differentiate themselves through product quality or branding.[6] Instead, competitiveness is achieved by improving productivity, reducing downtime, optimising equipment utilisation, and minimising energy and labour costs. In this context, autonomous technology becomes a key strategic tool for maintaining profitability.

Another characteristic that sets mining apart from many other industries is that nearly everything that is produced is eventually sold. Companies may temporarily stockpile extracted material during downturns to wait for more favourable prices, but they rarely face the structural overproduction seen in industries such as clothing or consumer goods, where unsold inventory is common. This means that, unlike in demand-driven markets, competition in mining revolves less around differentiation and more around cost control

[4] This section is informed by discussions with industry representatives throughout the work with this thesis and documented as part of the broader set of field notes (see Section 4.2.4).

[5] See Chen and Yang (2022) for an analysis of the transition from annual benchmark pricing to spot-index-based quarterly contracts in the iron ore market.

[6] There are, of course, possibilities for differentiation at later stages of mineral processing. For instance, the production of CO_2-reduced pellets or sponge iron can give steel producers greater flexibility in navigating market cycles and emission constraints, especially in periods of high demand. In downturns, however, cheaper feedstock may prevail despite higher emissions. Such opportunities for strategic positioning primarily arise in processing, whereas in extraction the scope for differentiation remains limited, with competitiveness largely driven by cost reductions and operational efficiency.

and internal efficiency. That said, this focus on cost-efficiency is a simplification. Other factors – such as transportation and logistics costs, ore grade, regulatory environments, energy access, labour market conditions, and, not least, geopolitical risk – also shape competitive advantage across regions and companies (Humphreys, 2011; Crowson, 2011). However, the overarching trend remains: companies with lower production costs tend to outperform their peers, especially in globally traded commodities.

At the same time, there is considerable asymmetry across the mining sector. Some companies are more technically advanced and better equipped to reduce cost through automation, digitalisation, and process optimisation. Others operate with older infrastructure and lower levels of digital integration. These differences affect not only cost structures but also their capacity to implement autonomous systems and take advantage of emerging technologies, further reinforcing the performance gap between leading and lagging sectors and companies.

2.2 From the European to the Swedish Mining Industry

Europe plays a significant but often underappreciated role in global mining. While it does not dominate the global production league table, the region offers a diverse geological portfolio – from iron, copper, and nickel in Scandinavia to critical raw materials across the EU (Eurostat, 2022). At the European level, mining has received renewed attention in light of the continent's ambitions to secure critical raw materials for the green and digital transitions. This includes policy initiatives aimed at reducing import dependencies, supporting domestic extraction, and fostering technological innovation through public–private collaboration.

Table 2.1 provides a comparative overview of the mining and quarrying sector in the European Union and Sweden. While the EU-level figures include a broad range of activities under NACE Section B – such as oil and gas extraction, industrial minerals, and quarrying – the Swedish figures refer specifically to active metal mines. This discrepancy highlights a key limitation in cross-national comparison: although Sweden's mining sector is relatively small in terms of number of enterprises, it plays a disproportionately large role in EU metal ore production, particularly in iron, zinc, and copper.

Table 2.1: Comparative overview of mining activity in the EU and Sweden

Region	**Number of mining enterprises**	**Key characteristics**
EU (NACE Section B: Mining and Quarrying)[7]	∼17,000	Employed approx. 371,000 people; value added approx. €64.1 billion (2022) (Eurostat, 2022)
Sweden (metal mines in production, 2023)	13	Accounted for 89% of EU iron ore production; major producer of copper, zinc, lead, gold, and silver (Rudebeck et al., 2024)

Although metal ore mining accounts for only 9.6% of the total turnover in the EU's mining and quarrying sector, a few countries play outsized roles in specific sub-sectors.[8] Sweden, for example, stands out in terms of iron ore extraction, while Bulgaria reported the highest national share of turnover in metal ore mining. This indicates that Bulgaria's mining sector is unusually specialised in metal production – in contrast to the majority of EU countries, where quarrying and energy extraction dominate. Overall, the largest contributors to total EU turnover from mining and quarrying were Norway (15.3%), Italy (14.2%), and Germany (13.6%). However, these countries differ substantially in what they produce: Norway is primarily focused primarily on crude petroleum and natural gas, whereas Italy and Germany have strong quarrying and construction material industries. High turnover, in other words, does not necessarily reflect a strong position in metal ore mining.

In terms of labour productivity, Sweden ranks among the highest, with an apparent labour productivity of €381,700 per person employed – more than twice the EU average of €172,700. This suggests a highly capital-intensive and technologically advanced mining model, where fewer workers produce more value. Moreover, Sweden's wage-adjusted labour productivity in the sector reaches 464.1%, indicating that even with relatively high wages, the sector remains highly competitive and efficient. This figure can be interpreted as evidence that Swedish mining companies generate sub-

[7] Includes all mining and quarrying activity classified under NACE Section B: coal, oil and gas extraction, metal mining, industrial minerals, construction materials, and mining support services. Metal ore mining (Division 07) accounts for only 9.6% of total sector turnover in 2022. As such, these aggregate figures likely understate Sweden's relative position in the EU's metal production.

[8] Statistics based on the latest data published by Eurostat under NACE Section B: Mining and Quarrying (Eurostat, 2022).

stantial returns on labour costs – a feature often associated with advanced automation and digitalisation.

Meanwhile, Poland, despite being the EU's largest employer in mining and quarrying with 38.4% of total employment, shows significantly lower productivity levels. This highlights a different industrial logic – one based more on volume and labour input than on capital efficiency. These disparities illustrate the diversity of mining strategies and specialisations within the EU, with some countries focusing on scale and labour intensity, while others – like Sweden – emphasise automation, technical skill, and efficient production systems.

While these figures highlight the diversity of mining strategies across the EU, they also point to broader structural and policy contexts that shape national priorities. Recent EU-level initiatives aimed at securing critical raw materials – through reduced import dependency, increased domestic extraction, and technological innovation – provide the backdrop against which national industries operate and research is prioritised. Sweden is deeply entangled with these developments. It is the EU's leading iron ore producer, responsible for around 89% of the region's output, and plays a key role in producing base and precious metals including copper, zinc, lead, gold, and silver.[9]

Structure and Geography

At the same time, Sweden has its own mining history, industrial structure, and policy landscape that influence how European strategies are interpreted and implemented. Most of Sweden's active metal mines – 13 as of 2024 – are concentrated in three major ore districts: Norrbotten, the Skellefteå field (Västerbotten), and Bergslagen (Rudebeck et al., 2024). These regions form the industrial backbone of Swedish mining and are deeply embedded in both national industrial traditions and broader European mineral strategies.

The Swedish mining industry consists of both underground and open-pit operations. The iron ore mines in Norrbotten – operated primarily by LKAB and Kaunis Iron – dominate production volumes, accounting for nearly all of Sweden's iron ore output in 2024. In Västerbotten, operations centre around sulphide ores such as copper, zinc, lead, and nickel, along with precious metals like gold and silver. Bergslagen's mining activities similarly focus on base metals, notably zinc and lead. In 2024, Sweden produced 80 million tonnes of ore, with a total sector turnover of approximately SEK 57 billion (Rudebeck et al., 2024).

[9]Statistics based on the latest figures published by the Swedish Geological Survey (SGU) in *Bergverksstatistik 2024* (Rudebeck et al., 2024).

Although Sweden contributes only about one percent of global iron ore production, it is responsible for 89 percent of the EU's total output. The country also accounts for around 10 percent of the EU's copper production and nearly half of the EU's lead and zinc output. These figures underscore Sweden's disproportionate significance as a metal ore producer within the EU, despite its relatively small number of active mines. Table 2.2 summarises Sweden's contribution to the EU's metal production, highlighting its dominant role in iron ore and substantial shares in lead and zinc.

Table 2.2: Sweden's share of EU metal production 2024 based on (Rudebeck et al., 2024)

Metal	**Sweden's share of EU production**	**Swedish production volume**
Iron ore	89%	25.0 Mt
Lead	46%	75,000 t
Zinc	45%	239,000 t
Copper	10%	77,000 t
Gold	n/a	7.5 t
Silver	n/a	430 t

Note: Percentages for gold and silver are not available because comparable EU-level production data are not published; SGU reports these only in relation to global production.

Occupational Roles

The Swedish mining industry includes both blue-collar and white-collar workers, covering a wide range of skill levels. In 2024, 64% of the workforce were blue-collar workers ("kollektivanställda"), while 36% were white-collar employees ("tjänstemän") (Rudebeck et al., 2024). This division reflects a longstanding structure in Swedish industry and informs how roles and responsibilities are distributed across sites.

The sector employs various types of engineers – such as mining-, geotechnical-, metallurgical-, environmental-, and drilling engineers – as well as geologists, technicians, and supervisors. In addition to these roles, there are two main categories of operators.

The first category consists of machine operators who handle equipment such as haul trucks, loaders, excavators, drills, blasters, and bulldozers. Depending on the mine, these operators may either be physically present on-site or operate machines remotely from a control room. In partially automated operations, tasks such as loading are often performed via tele-remote control, as human operators still tend to outperform autonomous systems in these functions. Once loaded, however, materials are typically transported autonomously, allowing a single operator to oversee multiple machines simultaneously.[10]

The second category consists of control room operators, whose responsibilities differ significantly from traditional machinery operation. Rather than controlling individual machines (or a limited number of machines), they oversee entire systems or subsystems related to production, safety, processing, or environmental management. Their work involves monitoring real-time data, adjusting parameters to optimise system performance, and responding to anomalies.

A third and equally essential category of work concerns maintenance – a domain that spans the upkeep of roads, infrastructure, production machinery, and digital communication networks. This work is distributed across multiple roles and requires a wide range of technical competences. Maintaining haul roads, for example, differs fundamentally from servicing automated machinery or calibrating network systems. As mining operations become more technologically complex, maintenance tasks are increasingly handled by specialised technicians and support personnel, some of whom resemble IT or tech support functions. These roles often demand advanced diagnostic skills, system-level understanding, and in certain cases, vendor-specific training. Maintenance is thus not only a logistical necessity but a knowledge-intensive component of contemporary mining operations.

While all three categories are essential to contemporary mining, it is primarily the first group of machine operators that faces staff reductions as autonomous technologies advance. In the Swedish context, however, there is a stated ambition to mitigate these effects by retraining and reallocating operators into control room and maintenance roles.

Work Environment and Regulatory Context

The work environment in mining is shaped not only by operational factors and technology, but also by the broader institutional and legal structures that regulate employment and labour relations in Sweden. A defining feature of this context is the so-called *Swedish model*, in which strong trade unions and collective agreements play a central role in regulating wages, work conditions, retraining, and restructuring processes (Kjellberg, 2009). These institutional arrangements operate in tandem with a robust legal framework – including labour laws and work environment regulations – that set minimum standards and ensure worker protection. Labour relations are

[10] See also Section 4.2.4 on field notes.

thus not only formalised, but also collaborative: changes in work and technology, including those brought about by automation, are typically subject to negotiation. This model has historically provided workers with stability and influence, and continues to shape how new roles and responsibilities are implemented and legitimised.

In Sweden, the concept of work environment (*arbetsmiljö*) typically encompasses the physical, psychological, and organisational conditions under which work is performed. This includes both objective conditions – such as risks, injuries, and exposures – and more subjective aspects related to how work is experienced. Swedish labour law and regulation explicitly recognise this duality, and employers are legally obliged to plan, organise, and evaluate work environments with both perspectives in mind.[11]

In the mining sector, traditional concerns have centred around physical hazards and occupational health risks. However, ongoing organisational shifts – including increased automation, centralisation, and the move from on-site work to control room environments – have introduced new challenges. One such shift is the changing occupational composition of the workforce: as physical work is increasingly replaced by system supervision and data monitoring, the proportion of white-collar roles grows in relation to blue-collar roles (Rudebeck et al., 2024). This has implications not only for the required skills, but also for how work is structured, experienced, and governed within increasingly digital and automated systems.

Extensive research on work environment issues has been carried out within Work Science at Luleå University of Technology (LTU) over many decades, and the mining industry has been a particularly important area of focus. This research has consistently shown that work environment in mining is not only about physical safety, but also about how work is organised, how workers are included in planning, and how technology and organisation are developed together. Studies have examined how new technologies reshape skills, roles, and even gender relations underground (Abrahamsson & Johansson, 2006, 2021), and how the attractiveness of mining work depends on organisational as well as technical solutions (B. Johansson & Johansson, 2014; B. Johansson et al., 2010). LTU researchers have also looked ahead, outlining scenarios for the future of mining and providing recommendations for how the industry can attract new generations of workers (Abrahamsson et al., 2009; J. Johansson et al., 2018). More recently, attention has turned to digitalisation and Mining 4.0, where the challenge

[11] Cf. Arbetsmiljölagen (SFS 1977:1160) [Work Environment Act]. See also Lag (1976:580) om medbestämmande i arbetslivet [Co-determination Act] regarding workers' rights to negotiation and participation. Arbetsmiljöverket, *Planering och organisering av arbetsmiljöarbete – grundläggande skyldigheter för dig med arbetsgivaransvar (AFS 2023:2).*

is to integrate new technologies with social and organisational practices in order to create safe, sustainable, and attractive workplaces (Lööw, Abrahamsson, & Johansson, 2019; J. Johansson et al., 2017; Lööw & Johansson, 2020; Lööw, 2021). Taken together, this body of research highlights the importance of understanding the work environment as an interplay between technology, organisation, and people.

In this thesis, I use the term *work environment* to refer to a broad set of conditions that shape how work is experienced and carried out. While the term includes aspects such as safety and health, the focus here is on how work is organised and experienced in the context of technological change – particularly in relation to operator roles, control room environments, and system supervision.

2.3 Design and Development of Autonomous Mining Systems

Drivers of Autonomous System Development

There are several interrelated drivers behind the development of autonomous systems in mining. While these vary somewhat between specific technologies and contexts, a number of recurring motives can be identified. These drivers are not only technological or economic, but also social and organisational, and should be understood as overlapping rather than discrete.

The most frequently cited driver is increased efficiency and reduced production costs. As discussed in Paper IV, this is particularly evident in the case of the autonomous haulage system, where continuous, uninterrupted operation enables optimised material flows and less downtime during breaks and turnovers. Even when autonomous machines operate at slightly lower speeds than human drivers, they tend to do so with greater consistency, resulting in smoother operation, reduced energy consumption, lower fuel or battery usage, and less wear on tyres and equipment.

A closely related driver is the reduction of human error (Paper IV). Machines do not get distracted, fatigued, or suffer lapses in concentration – they do not check their phones during operation, lose focus, or deviate from defined routines. As such, automation can offer improved reliability and predictability in production processes.

Labour cost reduction is another underlying rationale (Paper IV). With autonomous systems, fewer operators may be needed to perform the same volume of work. While this does not eliminate the need for human involvement, it can shift work from manual operation to remote monitoring, system oversight, or troubleshooting. In some cases, this shift leads to a modest reduction in personnel, but the overall effect on staffing levels is often limited. New tasks related to system maintenance, coordination, and exception handling tend to emerge alongside automation, complicating the assumption that labour costs will decrease in any straightforward way.

A further driver – and one that is particularly relevant in the mining context – concerns occupational safety. Mining remains a hazardous industry, with risks ranging from slips and falls to serious injuries and fatalities. Autonomous systems offer a means of improving safety by physically removing operators from these sometimes dangerous environments, such as haul roads, underground headings, or blast zones. This reduction in exposure has clear ethical significance, but also practical and economic consequences. Workplace accidents – especially fatal ones – are not only tragic for those directly affected; they are also costly for companies and can have far-reaching effects. When they occur, the consequences often extend well beyond the local site. Such events echo throughout the industry, drawing national and international scrutiny, shaping public perception, and in some cases influencing regulatory frameworks.

In Sweden, the number of workplace accidents in the mining sector is relatively low by international standards, but incidents with serious consequences do occur (Blank, Andersson, Lindén, & Nilsson, 1995). Reports from the Swedish Work Environment Authority and industry sources frequently highlight occupational safety as a key driver for technical development, including automation (Lööw & Nygren, 2019). Historical studies also suggest that the relationship between technological development, and accident rates is conditional rather than linear: while mechanisation initially raised risks, later automation contributed to reducing fatalities (Blank, Diderichsen, & Andersson, 1996). In this sense, improved work environment conditions are not only a desirable outcome, but also a strategic argument for investment in new technologies. The literature thus underscores both the potential and the ambiguity of technological change in mining. Safety improvements cannot be taken for granted, but depend on how new systems are designed, implemented, and integrated into existing work practices.

Taken together, these drivers suggest that autonomous systems are not introduced based on a single rationale, but rather on a convergence of goals: reducing cost, increasing efficiency, and enhancing safety. Although the relative weight of these drivers may vary between companies and projects, they form a broadly shared logic underpinning the push toward autonomous system development in mining.

Technological and Organisational Challenges

The conditions outlined above – particularly the high variability of mining environments – present a number of technological and organisational challenges. From the perspective of mining companies, this variability makes long-term technological decisions particularly complex. One key criterion for selecting which systems to invest in is adaptability – the ability of a solution to be integrated into existing operations and modified over time. To meet these needs, mining companies increasingly prioritise modularity, standardisation, and interoperability in both hardware and software.[12] Modularity allows individual components to be replaced or upgraded without overhauling entire systems. This is often expressed in the form of open interfaces, interchangeable machine modules, or system architectures that allow for vendor-specific add-ons. Standardisation helps reduce integration costs and facilitates collaboration across departments, suppliers, and partners. Adaptability ensures that systems can evolve in step with the mine's changing conditions and requirements.

A further technological challenge relates to the increasing software orientation of autonomous and digital systems. As these systems become more complex, they shift from being primarily mechanical or electrical – where functionality is embedded in physical components – to being governed by software. This transformation elevates the importance of OEMs and technology providers specialising in software, data infrastructure, and algorithm development. Consequently, mining companies become more dependent on external partners for critical functions such as system configuration, updates, cybersecurity, and ongoing support. This shift can create new challenges in terms of knowledge asymmetries, coordination, and long-term control over system evolution. These asymmetries arise partly because software is often proprietary and rapidly evolving, making it difficult for mining personnel to maintain internal expertise or fully understand how systems function *under the hood*.

At the organisational level, these changes require new forms of expertise, updated routines for maintenance and troubleshooting, and reconfigured roles within the organisation. The increasing involvement of external actors in core operational systems also places new demands on collaboration, contract management, and technical governance. In this context, different strategic preferences emerge among mining companies. Some prefer to acquire autonomous systems as a service, meaning that support, maintenance, and system updates are provided by the supplier as part of an ongoing agreement.[13] Others aim to retain knowledge in-house, seeking to build internal

[12]See also Section 4.2.4 on field notes.
[13]See also Section 4.2.4 on field notes.

competence and reduce long-term dependence on external vendors. These strategic choices reflect different risk assessments and organisational priorities, and they influence how responsibilities, costs, and competencies are distributed over time. Overall, these dynamics blur traditional boundaries between internal and external expertise and call for a rethinking of how mining companies manage technological transitions within complex organisational systems. They may also have implications for established forms of workplace cohesion, union representation, and the division of responsibility between the company and its contracted partners.

Arenas and Practices of Autonomous System Development

The development of autonomous systems in mining unfolds across multiple sites and involves a variety of stakeholders. Rather than being directed by a single actor, it takes shape through distributed networks of collaboration that bring together mining companies, OEMs, universities, and software developers. This section gives an overview of where, how, and by whom such development typically occurs, identifying key arenas, approaches, and organisational constellations that influence the trajectory of autonomous system design. Development in this context is not only technical but also profoundly social, emerging from interactions between engineers, designers, operators, and decision-makers working across organisational boundaries. These interactions form a field of practice in which design rationales are negotiated, solutions tested, and shared understandings gradually stabilised.

Mining companies often define operational needs or initiate pilot projects, whereas OEMs play a key role in core technological development, investing heavily in digital architectures that are later adapted for client environments. Collaborative arrangements between these actors illustrate an ongoing trend towards software-driven innovation in mining automation, where functions such as navigation, data integration, and fleet coordination are increasingly embedded in software rather than mechanical design. In this setting, universities and software developers contribute complementary expertise, including simulation, data analytics, and human–system interaction.

Unlike traditional mechanisation, which focused on assisting manual tasks through machinery, the design of autonomous systems must account for complex factors such as adaptability to different ore body conditions, real-time decision-making, and safety in mixed human–machine environments. Testing usually occurs through pilot projects managed by mining companies or in collaboration with other stakeholders, where systems are refined in response to real-world operational challenges. Some OEMs operate their own underground test facilities that replicate mining conditions, enabling controlled yet realistic experimentation with drilling, hauling, and blasting. These facilities serve simultaneously as demonstration sites for customers, development environments for new technologies, and platforms for validating performance.[14] They allow OEMs to advance product development independently of specific customer projects while showcasing system capabilities to potential clients.

Development activities take place in a range of organisational settings. Some mining companies pursue in-house development within their own R&D departments, focusing on testing technologies and adapting solutions to site-specific needs. This includes integration with local infrastructure, production systems, and safety requirements. For instance, during fieldwork I observed experiments with autonomous drones for muck-pile detection after blasting, where companies sought to integrate drone-based scanning into existing workflows to improve fragmentation analysis and operational efficiency. In such cases, adaptability refers to the technical system's capacity to interface with site-specific practices, whereas interoperability concerns its ability to function across different platforms and vendors.

Other development efforts take the form of project-based collaborations, typically centred on pilot projects in which new systems are tested and refined under production-like conditions. These projects bring together mining companies, OEMs, universities, and software firms, often supported by national or European innovation programmes. Within these constellations, mining companies contribute operational knowledge and provide access to test environments, while OEMs and software developers supply technical expertise and system integration capabilities. Academic partners may develop evaluation frameworks, conduct data analysis, or support standardisation efforts. Through these joint activities, autonomous mining systems evolve through iterative exchanges between technical innovation, operational experience, and organisational learning.

Beyond project-based collaborations, sector-wide coordination and knowledge exchange occur in more formalised, trans-organisational arenas such as conferences, working groups, and industry networks. These spaces provide platforms for coordination and knowledge exchange across organisational boundaries. Globally, examples include the Global Mining Guidelines Group (GMG), a not-for-profit organisation that facilitates global, multi-stakeholder collaboration to accelerate and de-risk the implementation of new practices, technologies, and processes in mining operations (Global Mining Guidelines Group, 2025), and the International Council on Mining and Metals, a CEO-led leadership organisation dedicated to improving sustainable development across the mining and metals sector (International

[14]See also Section 4.2.4 on field notes.

Council on Mining and Metals, 2025). In Sweden, notable examples include Svemin (the Swedish mining and mineral industry organisation), which acts as both a lobbying organisation and a collaborative platform (Svemin, 2025), and its Health & Safety Committee (GRAMKO), which brings together actors from industry, labour, and academia to discuss work environment, safety, and technology issues. These groups often serve as early arenas for identifying sector-wide concerns, formulating common goals, and aligning industry perspectives on emerging technologies.

In these arenas, a range of actors – including mining companies, OEMs, researchers, consultants, and other stakeholders – come together to identify industry needs, harmonise practices, and co-create guidelines for emerging technologies. The notion of "co-creation" reflects more than just consensus-building – it implies shared authorship of how problems are defined, what solutions are prioritised, and what standards are considered legitimate. Conferences are held regularly and typically feature workshops that feed into the production of white papers and technical roadmaps. The GMG, for instance, plays an active role in shaping standardisation and implementation trajectories for autonomous systems in mining (e.g. Global Mining Guideline Group, 2024). These trans-organisational arenas influence design trajectories not only by developing shared guidelines, but also by facilitating knowledge exchange, aligning terminology, and prefiguring design expectations across the industry – shaping how problems are framed and what solutions are considered viable. These arenas are also shaped by subtle tensions between collaboration and competition, where different actors – with varying resources, priorities, and market interests – seek to influence how problems are defined, which use cases are prioritised, and whose perspectives are embedded in emerging solutions. An example of this dynamic is highlighted by Burgess-Limerick (2025), who notes that GMG's guidelines for the implementation of autonomous systems tend to privilege technical and engineering perspectives, while the role of humans is acknowledged only as of peripheral importance. While these dynamics are not always visible on the surface, they play an important role in structuring the design space and defining the parameters of technological change.

A final example illustrates some of the challenges that can arise in the collaborative development of autonomous mining systems. During the final demonstration of the EU project I was involved in (see Section 4.1.2), a fully autonomous[15] loading cycle was successfully performed and widely celebrated as a major milestone. Yet, as one senior expert later remarked, similar achievements had already been made elsewhere, prompting questions

[15]This was how it was described within the context of the project. It included bucket filling, transportation to the dump zone, and a return to the loading position without human involvement.

about what the project actually contributed. The project was coordinated by an OEM in mining technology, what was formally presented as collaborative research increasingly resembled a product development effort centred on that OEM's existing technology. This example highlights a recurring challenge in innovation-oriented collaborations: when different stakeholders pursue their own technological and institutional agendas within ostensibly open frameworks, collaborative development can become entangled with diverse strategic interests and priorities. Such dynamics reveal how technical and social dimensions of innovation are deeply intertwined, as each actor's goals, resources, and organisational logics shape what kinds of innovation are promoted.

3 Theoretical Foundation

This chapter outlines the theoretical foundation of the thesis. Two theoretical perspectives are central to the analysis and discussion: Sociotechnical Systems Theory and the theory of Communities of Practice. Together, they provide complementary lenses for understanding how autonomous mining systems are developed, implemented, and embedded in work practice.

In addition, the chapter draws on insights from research on automation and autonomous systems. This literature is important for theoretical context and clarity. The following section therefore outlines these insights before turning to the two main theoretical perspectives of the thesis.

To orient the reader at the outset, Table 3.1 summarises the primary theoretical lenses mobilised across the four papers included in the thesis. The intention is not to pre-empt the analyses, but to make explicit how the theoretical foundation of this thesis relates to the appended papers and the broader argument developed in this chapter concerning the connection between Sociotechnical Systems Theory and the theory of Communities of Practice as complementary perspectives for illuminating how structural and social processes shape the implementation of autonomous systems.

3.1 From Automation to Autonomous Systems

This section positions the thesis within research on automation and autonomous systems and introduces the key design logics that inform its analytical framing. It first revisits Bainbridge's Ironies of Automation, then outlines three canonical *automation logics* – the *Default Strategy*, the *Fitts' List Approach*, and *Adaptive Approach to Automation* – and concludes with a conceptual clarification of how automation and autonomous systems are understood in this thesis.

3.1.1 Ironies of Automation

Research on human–automation integration has a long history across domains such as aviation, process industries (e.g. Parasuraman, Sheridan,

Table 3.1: Theoretical frameworks across the four papers

Paper	Primary theoretical lens	Note
Paper I	Sociotechnical Systems Theory	Not explicitly articulated, but provides the underlying analytical orientation.
Paper II	Sociotechnical Systems Theory	Provides the primary background framing.
Paper III	Communities of Practice (É. Wenger, 2008)	Focus on mutual engagement, joint enterprise, and shared repertoire in practice.
Paper IV	Sociotechnical Systems Theory	Draws on Balance Theory (Smith & Sainfort, 1989; Carayon & Smith, 2000) within the broader sociotechnical tradition to understand changes in work, including the reconfiguration of tasks and roles.

& Wickens, 2000; T. B. Sheridan & Parasuraman, 2005; Endsley & Kiris, 1995). A recurring lesson from this body of work in relation to work is the risk that operators become "out of the loop" when their involvement is reduced to residual or occasional interventions. Such situations are problematic because they weaken operators' skills, awareness, and ability to act effectively when needed. Given these risks, examining how end users are included – or excluded – in automation is crucial, since marginalisation can erode both safety and system performance.

One of the most influential contributions to this debate is Lisanne Bainbridge's seminal brief paper titled The Ironies of Automation (1983). In it, she argued that several ironies arise in the development and implementation of automation in industrial processes, inadvertently creating challenges for the human operator rather than alleviating them. The paper is considered a landmark that has influenced automation design principles, regulatory frameworks, and accident investigations. More than forty years later, its insights continue to shape academic discussions and practical applications across fields such as aviation, public services, AI, and robotics. Later writings (e.g. Baxter, Rooksby, Wang, & Khajeh-Hosseini, 2012; Strauch, 2018; Hancke, 2020) confirm that many of the ironies Bainbridge identified – such as degraded operator skills, over-reliance on automation, and difficulties in take-over situations – remain unresolved. They also point to new challenges, including automation bias, complacency, and the growing opacity of complex digital systems. Taken together, this body of work demonstrates that although Bainbridge's paper is more than forty years old, the issues it raised are still pressing today and continue to inform debates on the design and use of automated and autonomous systems.

The classical aim of automation is, according to Bainbridge (1983), to replace human control with automation, thereby eliminating problems associated with human operators. However, the paper argues that this perspective often produces the opposite effect. Rather than being replaced, humans remain essential for the supervision, adjustment, and maintenance of these seemingly automatic systems. This need becomes particularly apparent as system complexity increases, requiring even greater human involvement. Bainbridge highlights two key ironies that emerge from the attempt to replace humans with automation.

The first irony is that designers often view operators as unreliable and inefficient, leading to efforts to eliminate their role. However, design errors can themselves become a major source of operational problems, sometimes creating more issues than the technology was intended to resolve. The second irony concerns the tasks that designers are unable to automate, resulting in an arbitrary collection of responsibilities that operators are still required to manage. Operators are frequently excluded from the design process of automation, which leads to a situation in which they are left with two primary categories of tasks related to automated systems (Bainbridge, 1983):

1. *Monitoring* – to ensure that the automatic system functions correctly.
2. *Take-over* – intervention in the form of manual control if the automatic system is not functioning correctly.

From these two primary categories of tasks, Bainbridge (1983) identifies and discusses several further ironic effects. For monitoring, Bainbridge highlights that humans are not well suited to directing visual attention towards sources of information for extended periods, particularly when little occurs or when changes are subtle. They easily become tired and distracted and therefore risk not being attentive in critical moments. The proposed solution to this problem is to incorporate an automatic control system linked to sound signals (and visual signals today). However, this introduces a vicious circle as it simultaneously creates the need to monitor whether the alarm system itself is functioning correctly. In other words, who monitors the monitoring system? This issue, in theory, extends *ad infinitum*.[16] Yet Bainbridge identifies a more serious irony in the fact that an automatic control system is introduced on the grounds that it performs monitoring more effectively than the operator, while the operator is still expected to monitor whether this automatic control system is working effectively.

For take-over, which concerns the task of intervening when the automatic system is not functioning properly, Bainbridge (1983) primarily discusses two ironies. The first relates to *manual control skills*, which can deteriorate when not regularly practised, particularly in terms of fine-tuned adjustments to gain and timing, potentially leading to oscillation in the system during take-over. If the system begins to oscillate, the operator may have to wait for feedback from the system. However, the operator is then in a position of uncertainty, unsure whether the feedback indicates a fault in the system or that the control action has been misjudged.

The effects of take-over involve cognitive skills, and Bainbridge highlights several problems associated with these. One is that effective take-over relies on retrieval from long-term memory, which in turn depends on frequency of use; the less frequently a task is performed, the less efficient the retrieval becomes. Another issue concerns the time required to build an understanding of the system's overall status. Manual take-over often occurs during disturbances, when the operator must make quick decisions based on limited information.

To address these challenges, Bainbridge proposes several technical innovations and ingenious approaches, emphasising the need to develop human–computer collaboration. This collaboration involves various forms of computer intervention in human decision-making, including providing instructions, mitigating errors, enhancing displays, and assisting operators during periods of high workload. Ultimately, the paper concludes that automation does not eliminate difficulties; rather, it can introduce new challenges. Bainbridge argues that further technological innovation and ingenuity – rather than classical automation – are the primary means of addressing these issues.

In sum, Bainbridge (1983) shows that attempts to use automation to remove operators rarely succeed; instead, striving for this often creates new and sometimes more demanding operator tasks. These tasks crystallised in two categories – monitoring and take-over – which remain central reference points for understanding human–automation interaction. These tasks capture the paradox that automation can reduce human involvement while simultaneously making it more critical in moments of disturbance.

[16]Although, in practice, several layers of fail-safe architecture are often argued to support redundancy in technological systems. This was a point made by the designers and developers who were part of the workshop study, published in Paper II.

This insight is essential for the present thesis, as it underscores the risks of marginalising operators in autonomous mining systems, including the danger of leaving them out of the loop, and provides a conceptual backdrop for analysing how their roles are reshaped in practice.

Together, these ironies motivate the need to ask how the design and development of automation technology is guided – a question that is taken up in the next subsection on automation logics.

3.1.2 Automation Logics

The development of automation is not only shaped by technical feasibility but also by underlying logics that guide decisions about what should be automated and why. These logics reveal different rationales for pursuing automation: from maximising efficiency by automating as much as possible, to allocating tasks based on the comparative strengths of humans and machines, to maintaining flexibility through dynamic sharing of control. Identifying these approaches is important because they influence how operator roles are envisioned in the design and development phase, and ultimately, how work is reconfigured – not by eliminating operators, but, as highlighted in the previous subsection, by reshaping their involvement in new (and sometimes unintended ways). In the following, I outline three such logics described by Parasuraman et al. (2000): the Default Strategy, the Fitts' List Approach, and the Adaptive Approach to Automation.

> **Def. 1.** *Default Strategy* – an approach to automation in which all tasks that can be automated are automated.

The first is known as the Default Strategy, which involves automating everything that can be automated, typically to increase efficiency or reduce production costs. As noted in Chapter 2, these objectives represent one of several general drivers of automation, and are not problematic in themselves. What makes the Default Strategy distinctive – and potentially problematic in the context of work – is the rather uncritical assumption that technology can, and will, resolve all problems. This logic aligns with what Bainbridge (1983) describes as the classical aim of automation. As discussed in the previous subsection, the result risks leaving operators with an arbitrary set of tasks that designers either cannot envision how to automate (Bainbridge, 1983), or that are too expensive or too complex to automate at the time (Parasuraman et al., 2000). The approach is technology-driven in the sense that it is the automation technology – rather than task demands or human capability – that defines the operator's role (Parasuraman & Riley, 1997). It has also been described as a technology-centred approach, aiming to optimise the capabilities of the system itself (Endsley & Kaber, 1999).

The second approach to automation is known as the Fitts' List Approach. It is grounded in the Tayloristic principle of placing the "right person in the right place" (cf. Taylor, 1911).

> **Def. 2.** *Fitts' List Approach* – an approach to automation based on the principle of comparative advantage, where tasks are allocated according to the relative strengths of humans and machines. Tasks that machines perform better are automated, whereas those better suited to human capabilities are retained as manual functions (Parasuraman et al., 2000).

This principle is operationalised through a comparison of human and machine capabilities – see Table 3.2 for the original list proposed by Fitts (1951), which outlines the abilities in which operators[17] surpass machines, and vice versa.

Table 3.2: Fitts' List

Operators surpass machines in the:

- Ability to detect small amounts of visual or acoustic energy
- Ability to perceive patterns of light or sound
- Ability to improvise and use flexible procedures
- Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time
- Ability to reason inductively
- Ability to exercise judgment

Machines surpass operators in the:

- Ability to respond quickly to control signals, and to apply great force smoothly and precisely
- Ability to perform repetitive, routine tasks
- Ability to store information briefly and then to erase it completely
- Ability to reason deductively, including computational ability
- Ability to handle highly complex operations, i.e. to do many different things at once

Fitts's classification suggests that operators are better at detection, perception, judgement, improvisation, inductive reasoning, and long-term memory, whereas machines exceed human performance in speed, power,

[17] "Humans" in the original text.

replication, computation, multitasking, and short-term memory. While the list may appear outdated given technological advances since its publication over 70 years ago, subsequent writings by De Winter and Dodou (2014) and De Winter and Hancock (2015) argue that its core distinctions remain relevant – though machines have since overtaken humans in areas such as detection, perception, and even long-term memory. The central logic of the Fitts' List Approach is that task allocation should be guided by comparative advantage – tasks best performed by machines should be automated, while those better suited to human capabilities should remain manual (Parasuraman et al., 2000).

The third and final approach to automation, according to Parasuraman et al. (2000), is known as the Adaptive Approach to Automation.

> **Def. 3.** *Adaptive Approach to Automation* – an approach to automation in which control and responsibility are dynamically shared between the operator and the system, based on intermediate levels of automation. Emphasising flexibility, the approach allows operators to delegate tasks and receive feedback, supporting engagement, effective intervention, and improved overall system performance (Parasuraman et al., 2000; Miller & Parasuraman, 2007).

A central idea of this approach is to keep the operator actively involved in the system. It emphasises the dynamic allocation of tasks and responsibilities between the operator and the autonomous system (Kaber, Wright, Prinzel, & Clamann, 2005). The approach rests on two core principles. First, neither the operator nor the automation should have exclusive responsibility for most tasks (Miller & Parasuraman, 2007). Instead, the division of labour should be structured around intermediate levels of automation. Second, the automation must be highly flexible during operation. Operators should be able to delegate tasks to the system and receive ongoing feedback about its performance.[18] Miller and Parasuraman (2007) further suggests that this delegation should resemble successful human-to-human interaction – involving varying levels of specificity, and potentially including constraints, stipulations, contingencies, and alternatives.

Flexibility in human–automation interaction has been associated with

[18] In the literature, a distinction is sometimes made between *adaptive* automation, where the system adjusts the level of automation in response to predefined triggers, and *adaptable* automation, where the operator retains authority to change the level of automation (Parasuraman et al., 2000; Miller & Parasuraman, 2007; Calhoun, 2022). This technical debate is beyond the scope of the present thesis, and the two are therefore treated as one general approach.

several potential benefits, including improved situational awareness, more accurate use of automation, better-balanced mental workload, increased user acceptance, and overall system performance (Parasuraman, 2000). Adaptive automation has thus been proposed as a strategy for mitigating human performance issues that arise in the context of advanced automation.

This approach offers a conceptual basis for analysing how automation alters the cognitive, behavioural, and skill-related demands placed on operators. It also provides insight into how design changes in automation can influence operator engagement, role clarity, and the capacity to intervene effectively when systems fail.

In sum, these three automation logics – the Default Strategy, the Fitts' List Approach, and the Adaptive Approach to Automation – illustrate different rationales that have historically shaped the development of automation. Each logic frames the role of the operator in distinct ways: either as a residual actor left with arbitrary functions, as a complementary partner whose strengths are preserved, or as an active participant dynamically sharing control with the system. For the purposes of this thesis, these logics are important not as prescriptive models but as analytical reference points. They highlight the underlying assumptions that guide how automation is pursued, and they provide a conceptual lens for examining how similar logics influence the design and implementation of autonomous mining systems and the reshaping of operator work.

These contrasting logics also prepare the ground for a conceptual bridge to autonomous systems. With these rationales in view, we can now clarify how the thesis relates automation to autonomous systems and why the latter imply a different kind of integration.

3.1.3 A Conceptual Clarification

Up to this point, I have used the concepts of "automation" and "autonomous systems" without offering a detailed clarification of what is meant by them, sometimes interchangeably. However, central to this thesis is the assumption that although the latter builds upon the former, their implications for work and organisation differ in significant ways. Whereas automation primarily concerns the delegation of specific functions to machines or software, autonomous systems entail a more complex redistribution of control, coordination, and decision-making within the work system.

The purpose of this section is not to provide exhaustive definitions, but to establish a clear theoretical point of departure for how these concepts are understood in this work. Clarifying how the concept of "automation" relates to "autonomous systems" is important for conceptual precision: while autonomous systems are at the core of the thesis, their meaning builds on and extends the concept of automation. In what follows, I outline how the two concepts are connected and why insights from classic automation research remain relevant for analysing operator work in contemporary mining. I then briefly elaborate on what is implied by the notion of "systems" in relation to autonomous systems.

Automation is commonly defined and understood as the use of machines, computers, and systems that can operate without human control. Bright wrote as early as 1958 that few words had been so *"twisted to suit a multitude of purposes and phobias"* as the then-new term automation (Bright, 1958, 4). By that time, the word had already been used to describe technical challenges, manufacturing goals, advertising slogans in various labour campaigns, and as a symbol of technological progress. Bright traces this confusion to the existence of multiple definitions of the term, a semantic ambiguity regarding what it means to *automate* – that is, to create automation technology – and an exaggeration of the capabilities and staffing requirements of automated plants.

One way to illustrate how the concept of "automation" relates to autonomous systems or technology is through the framework of *Levels of Automation*. Various taxonomies of automation levels exist, and in this thesis I will use the taxonomy proposed by T. Sheridan and Verplank in (1978) for illustrative purposes. This taxonomy outlines ten levels of automation (LOA) for decision and action selection. See Table 3.3 for an overview.[19]

Table 3.3: T. Sheridan and Verplank's (1978) LOA Taxonomy

1	Operator does it all
2	Computer offers alternatives
3	Computer narrows down alternatives to a few
4	Computer suggests a recommended alternative
5	Computer executes alternative if operator approves
6	Computer executes alternative; operator can veto
7	Computer executes alternative; informs operator
8	Computer executes selected alternative; informs operator if asked
9	Computer executes selected alternative; informs operator if it decides to
10	Computer acts entirely autonomously

I use this taxonomy only to highlight a few points about automation and the operator's role. First, the role of operators in systems based on automation varies depending on how advanced the system is – or, to use T. Sheridan and Verplank's (1978) terminology, the level of automation

[19]The table also draws on Miller and Parasuraman's (2007) interpretation of T. Sheridan and Verplank (1978).

the system possesses. The operator is excluded from decision and action selection only at the highest level of automation, which, in fact, constitutes autonomous functioning. With this understanding, we can see how the concepts relate to each other, that the latter is a more advanced version of the former. I therefore find that research, insights, and lessons developed in relation to *automation* – including its challenges and implications for operator work – remain, in many cases, highly relevant to the study of autonomous systems in this thesis.

"Autonomous" suggests a form of self-governance and the capacity to make and act on decisions independently. Parasuraman (2000) have proposed a definition of fully autonomous systems as those that are highly reliable in their error-handling capabilities. Such systems must possess both the ability and the technical capacity to manage large numbers of potential anomalous situations effectively and efficiently, as well as the ability to respond to unforeseen events.

However, both research and industry use the term "autonomous" to refer to a wide range of systems, technologies, and artefacts. This closely resembles the conceptual confusion surrounding the term "automation" that Bright expressed frustration over in the late 1950s. Bright addressed the issue by drawing on Wittgenstein's (1958) thesis that the meaning of words is determined by their general usage. Accordingly, automation simply refers to *"something significantly more automatic than previously existed in that plant, industry or location"* (Bright, 1958, 6).

Drawing on a similar logic, autonomous systems can be understood as those that operate significantly more autonomously than previously existed in that plant, industry, or location.[20] This interpretation reflects how the concept is typically understood and applied within the mining industry, where it is used to describe systems, technologies, or machines that perform tasks with an increased level of independence from direct human control. The same understanding is also present in parts of the research literature, where "autonomous" is often used in this relative, comparative sense. However, as will be argued below, the distinction is not merely semantic: the shift from automated to autonomous systems introduces opportunities for

[20]There are several related concepts associated with autonomous systems in mining. Sometimes the term *fully* is added, and in other discussions, expressions such as *zero-entry* mining – indicating that no humans will enter the mine due to autonomous systems – or *lights-out* mining, where production is so autonomous that the lights could, in principle, be turned off, are used. The issue with such conceptualisations is that they often assume no need for maintenance or that the system will function perfectly without disturbances, which is rarely the case outside theoretical discourse. In my view, these concepts do not, in practice, add anything substantially beyond the definition stipulated here. There are, however, discussions about autonomous maintenance in mining. At the time of writing, these remain conceptual and lack a clear, practical solution.

new forms of integration and interdependence that give rise to emergent properties at the system level.

What arises in this shift cannot be reduced to a set of isolated technical improvements or discrete control functions; instead, it involves the emergence of a qualitatively new configuration of relations between humans, machines, and organisational structures. In other words, something new emerges at the system level that is not present in the individual components.

This is where the second part of the concept becomes essential – the notion of systems. Whereas automation typically refers to the control or delegation of specific tasks, autonomous systems extend beyond this by integrating multiple technological and human components into a coordinated whole. The system encompasses machines, software, operators, and organisational routines that interact continuously to sustain production. Following a classic systems perspective, the whole becomes more than the sum of its parts: its behaviour and outcomes emerge from the interdependencies among the elements rather than from any single component in isolation.

In this sense, autonomous systems signify not only a quantitative expansion of automation, but also a qualitative transformation toward higher levels of integration and interdependence between the technical and the social. This understanding – that such systems generate emergent properties through interaction, rather than only through simple aggregation – underpins the analytical approach taken in this thesis and informs the subsequent examination of how these technologies reshape operator work and organisational practice.

3.1.4 Summary of Implications

Taken together, the three parts of this section establish how the thesis understands and analyses autonomous mining systems. First, the discussion of the ironies of automation shows that attempts to reduce human involvement typically reconfigure rather than remove it. The outcome is a division of labour centred on monitoring and take-over, tasks that reveal ergonomic and cognitive limitations. These dynamics underscore the persistent risk that operators become marginalised in autonomous systems, even though their involvement remains essential.

Second, the automation logics (Default Strategy, Fitts' List, Adaptive Automation) reveal distinct rationales that shape how functions and authority are allocated between humans and machines. Each logic carries different implications for operator roles, competence requirements, workload, and the conditions for successful intervention during disturbances. In this thesis, these logics are used as analytical reference points to interpret design choices and implementation trajectories in mining.

Third, the conceptual clarification shows that "autonomous systems" extend earlier ideas of automation while introducing a different kind of integration: not merely more automated functions, but coordinated constellations of machines, software, operators, and other subsystems. This anchors the thesis in a precise use of concepts and motivates why insights from classic automation research remain relevant.

In sum, this section provides the conceptual grounding for the analyses that follow. It links macro-level design logics to the social and technical integration of systems and to the micro-level dynamics of operator work. The subsequent sections of this chapter will introduce the two core theoretical foundations of the thesis – Sociotechnical Systems theory and communities of practice – which together provide the primary lenses for the analyses that follow.

3.2 Sociotechnical Systems Theory

With this conceptual background in place, I now turn to the first theoretical lens: Sociotechnical Systems Theory.

Sociotechnical Systems Theory has its roots in the broader tradition of sociotechnology. While the two terms are sometimes used interchangeably, it is important to distinguish between them. Sociotechnology emerged as a design tradition in the mid-twentieth century through the work of the Tavistock Institute, particularly the seminal study of the social and psychological consequences of introducing the longwall method in coal mining by Trist and Bamforth (Trist & Bamforth, 1951).[21] Its central aim was normative – to humanise work, democratise workplaces, and promote improvments of social and technical aspects of work systems – yet these efforts also had important analytical and theoretical implications that informed the later development of Sociotechnical Systems Theory.

This tradition was closely tied to experiments with new forms of work organisation, such as semi-autonomous groups, and carried a strong commitment to values of workplace democracy and participation (Mumford, 2006). Because these values and principles are inherently normative, sociotechnology has always been susceptible to political interpretation, which has contributed to fluctuations in its popularity over time. For readers

[21] This research was among the first projects conducted by the Tavistock Institute of Human Relations in London (Trist, 1981). The Tavistock group, established in 1946 with support from the Rockefeller Foundation, aimed to integrate psychological and social sciences to improve both individual well-being and work organisation (Mumford, 2006). Their work was closely linked to the development of action research and the founding of the journal *Human Relations*.

interested in the sociotechnical design principles, see Cherns (1976) and Mumford (2006).

Sociotechnical Systems Theory, by contrast, represents a more general analytical theory. Although early sociotechnical research was not framed explicitly as systems theory, later reflections by Trist (Trist, 1981) more clearly articulated the systems perspective and laid the foundations for the theory as it is understood today. Carayon et al. (2015, 550) define a sociotechnical system as *"the synergistic combination of humans, machines, environments, work activities, and organizational structures and processes that comprise a given enterprise."* From this perspective, the focus is not on prescribing particular forms of work design, but on understanding how technical and social elements interact, and how this interaction shapes system performance, work practices, and organisational outcomes.

What today may appear as a rather self-evident observation – that social and technical dimensions of work are deeply intertwined – was not always recognised. The very emergence of Sociotechnical Systems Theory can, in broad terms, be understood as a response to this absence. As Ropohl (1999) notes, a general understanding of technical society was largely missing: engineers often failed to consider the social implications of their work, while social scientists typically lacked sufficient technical knowledge. Although this characterisation may seem outdated today, it highlights a historically significant concern and helps explain why integrative frameworks were needed to bridge the gap between technological development and social understanding. Systems theory, according to Ropohl, offered precisely such a framework – bringing together sociology and technology in the *"technization of society and the socialization of technology"* (Ropohl, 1999, 191).

In this thesis, I acknowledge the normative origins of sociotechnology, but I do not adopt it as a design programme. Rather, I draw on Sociotechnical Systems Theory analytically, which provides concepts and sensitivities that help illuminate how autonomous mining systems are designed and implemented, how they affect operator work and their implications for organisational dynamics, and how technical and social elements must be considered in relation to one another.

Sociotechnical Systems Theory is not the only theory available for analysing the relationship between technology, work, and organisation, nor is it without criticism. For instance, it has been described as too broad and conceptually vague (Klein, 2014), and as overly schematic in ways that risk overlooking the micro-level dynamics of technology use and implementation (Bostrom & Heinen, 1977). Nevertheless, I consider it a useful point of departure for this thesis. The strength of the sociotechnical perspective lies in its breadth: it offers an overarching lens that enables both technical and social dimensions of autonomous systems to be considered in tandem.

In particular, it provides a way of linking technological features and design logics with the organisational and social arrangements in which they are embedded. This makes it well suited as a broad theory that spans the overall purpose of the thesis. It provides a way of situating the underlying assumptions, logics, and priorities that guide the design and development of autonomous mining systems within a wider frame that accounts for how technical and social systems interact and co-evolve.

At the same time, and as noted above, the theory has limitations. It is less well equipped to capture the fine-grained dynamics of implementation and the social processes through which technology is integrated into everyday work. For this reason, the thesis complements the sociotechnical perspective with an additional lens. Drawing on Wenger's (2008) theory of Communities of Practice makes it possible to examine more closely the social aspects of the implementation process of autonomous mining systems. In this sense, Sociotechnical Systems Theory offers the overarching theory for understanding the interplay between social and technical systems, while Communities of Practice provides the conceptual tools to analyse the social processes through which these changes are enacted. The latter perspective is introduced separately in a later section of this chapter.

The presentation of the Sociotechnical Systems Theory is structured into three main subsections. The first addresses the principle of joint optimisation and how it can be connected to different automation logics. The second turns to the operator perspective, with particular attention to the ways in which automation can marginalise operators and what this means for the functioning of sociotechnical systems. The third explores the multi-level dynamics of sociotechnical systems, showing how the implementation of autonomous technologies reverberates across organisations. The section concludes with a short summary of the key implications.

3.2.1 Joint Optimisation and Automation Logics

Sociotechnical Systems Theory begins from the observation that all work involves an interplay between technology and people. Rather than treating these as separate domains, the theory conceives of them as two interdependent subsystems: the technological subsystem and the social subsystem (Mumford, 2006). The technological subsystem includes equipment, machines, tools, and the work organisation (Carayon et al., 2015), while the social subsystem encompasses individuals, teams, coordination, control, and management. These two subsystems are distinct, yet symbiotic, and together they form the sociotechnical system as a whole.

Sociotechnical theory further holds that these subsystems are always embedded in a wider environment that influences their behaviour and functioning (Mumford, 2006; Burke, 2008). At the core of such subsystems lies a basic unit of activity: a set of interdependent tasks that together form a functioning whole, i.e., the sociotechnical system's activity (Burke, 2008). This stands in sharp contrast to Scientific Management, which sought to improve efficiency by decomposing work into narrowly defined, specialised components (Taylor, 1911). From a sociotechnical perspective, however, the emphasis was in the opposite direction: advocating more integrated and coherent forms of work in which interdependent tasks are combined into a meaningful whole of social and technical elements. In this sense, any work system that depends on both humans and technology can thus be understood as a sociotechnical system.

It is not only that sociotechnical systems consist of two distinct subsystems, but also that these subsystems can function well or poorly depending on how they are designed. A technically advanced system may fail if the social organisation around it is weak, just as a socially well-functioning organisation will struggle if the technical arrangements are inadequate. From a sociotechnical perspective, the overall performance of such a system therefore hinges on how the social and technical subsystems are aligned with each other and with the demands of their environment (Mumford, 2006).

This idea is captured in the principle of *joint optimisation*, which holds that both subsystems must be optimised and given equal weight if the sociotechnical system as a whole is to function well. A sociotechnical system that privileges one subsystem at the expense of the other risks producing negative outcomes. Trist and Bamforth's classic study of coal mining illustrates this dynamic: the then newly introduced longwall method optimised the technical subsystem but neglected the social subsystem, leading to poor results (1951). In other words, the quality of a sociotechnical system depends not only on the technologies it employs but also on how work is organised, how teams are structured, and how social relations are taken into account.

In practice, the idea of joint optimisation also implies a continuous striving for improvement. For the social subsystem, optimisation can take many forms, ranging from later-stage efforts such as workplace development initiatives or systematic work environment management, to earlier considerations about how tasks and responsibilities are defined when new technologies are introduced. For the technical subsystem, improvement may involve both optimising existing technologies and introducing new ones. A central issue, then, is how technological development is driven, and what implications this has for the balance between the two subsystems.

One way to approach this issue is through the notion of automation logics (discussed in Section 3.1.2). These logics describe different strategies for allocating functions between humans and machines, and can be understood as design orientations that implicitly prioritise the social or the technical subsystem to varying degrees. The Default Strategy (Def. 1) tends to privilege the technical subsystem, risking the kind of imbalance that sociotechnical theory warns against. The Fitts' List Approach (Def. 2), by contrast, is more consistent with the principle of joint optimisation, as it considers complementarities between human and machine capabilities and offers a way of keeping operators meaningfully engaged in the sociotechnical system. The Adaptive Approach to Automation (Def.3) builds on a similar rationale but introduces flexibility through dynamic reallocation of functions, thereby also presenting a possible means of keeping operators active and supporting system resilience and integration.

From a sociotechnical perspective, these automation logics are not merely technical design choices; they represent different ways of configuring the relationship between social and technical subsystems. Analysing them through the lens of joint optimisation thus provides a language for examining how autonomous systems may strengthen or undermine the overall functioning of work systems. In practice, these logics do not necessarily appear in isolation; elements of each can be combined in different ways. What matters most, according to this view, is whether such combinations are arranged in ways that remain consistent with the principle of joint optimisation of both the social and the technical subsystems over time.

3.2.2 Operators in Autonomous Systems

What, then, is the role of the operator in autonomous systems? According to Bainbridge (1983), automation leaves operators with two primary tasks: to monitor systems and to take over in the event of a failure. These roles can appear residual and marginal, yet they are in fact crucial for the robustness of the sociotechnical system. Without the ability to oversee and intervene, the system risks vulnerability.

From a sociotechnical perspective, this marginalisation can be problematic. If operators are reduced to residual functions, this interdependence can be undermined and the system as a whole risks becoming fragile. Ropohl (1999) has argued that technological functions are frequently introduced with the aim of substituting for human ones. Yet, as he shows, such substitution has limits: technical artefacts may replicate certain functions, but the sociotechnical system still relies on human actors for interpretation, adaptation and goal-setting. Contemporary sociotechnical safety frameworks also highlight this point: safety emerges from the interaction between people, technologies, and organisations, not from any one element alone (Carayon et al., 2015).

The assumptions that underpin design logics for automation (Section 3.1.2) also implicitly define operator roles. The Default Strategy (Def. 1) tends to exclude operators, while the Fitts' List Approach (Def. 2) frames them as complementary resources, and Adaptive Approach to Automation (Def. 3) highlights flexibility but at the cost of increased demands. As Baxter and Sommerville (2011) note, design approaches always embed assumptions about how social and technical elements are expected to interact. These implicit definitions matter, in that they shape what kinds of work roles are foreseen when autonomous systems are created and implemented.

In practice, however, these roles are never fixed. Once implemented, when autonomous systems encounter use, operators find ways to make sense of the technology, create new routines, or, conversely, experience uncertainty and gaps (see Paper III). Within a sociotechnical vocabulary, this means that the social subsystem renegotiates its relation to the technical subsystem during implementation. Recent mining research shows how this negotiation also entails risks: marginalising operators in supervisory roles can introduce new hazards and vulnerabilities, rather than eliminating them (Hassall, 2022). These dynamics suggest that operator roles cannot be treated as residual or secondary but must be understood as central to the sociotechnical functioning of autonomous mining systems.

This is also a question of long-term sustainability. Industry 4.0 is frequently framed in terms of vertical, horizontal, and end-to-end integration, but sociotechnical analyses have shown that such integration will only be sustainable if both human and technical subsystems are optimised together (Sony & Naik, 2020). From this perspective, the marginalisation of operators is not simply a matter of task allocation. It is a systemic issue that directly affects the resilience and viability of sociotechnical systems. For this reason, examining how operators' roles are shaped, constrained and renegotiated in autonomous mining is crucial to the overall purpose of this thesis: to understand the implications of autonomous systems for operator work.

3.2.3 Multi-level Dynamics of Sociotechnical Systems

The implementation of autonomous systems does not only affect discrete tasks or operator–machine interaction, but reverberates across the wider organisation. Organisational structures, management practices, and external demands shape how new technologies are adopted and how their consequences unfold. From a Sociotechnical Systems Theory perspective, this means that the effects of autonomous systems cannot be understood at a single level alone: they are distributed across interdependent layers of the work system. This multi-perspective view is central to the sociotechnical approach, and provides a rationale for looking beyond immediate operational changes to the broader dynamics of organisations and their environments (Ropohl, 1999).

One influential development in this tradition is Smith and Sainfort (1989)'s Balance Theory, later extended by Carayon and Smith (2000). Balance Theory emphasises work from a systems perspective, conceptualising it in terms of five elements: (1) the physical environment; (2) work tasks, including job demands and content; (3) technology; (4) organisational factors such as structure, culture, communication, and management; and (5) the individual, including aspects such as personality, health, skills, experience, motivation, goals, and needs.

The theory argues that these elements must be jointly considered to improve the performance, health, and safety of work systems (the sociotechnical system). Two aspects of balance are highlighted (Carayon & Smith, 2000). The first concerns the overall balance of the system: if an organisation focuses exclusively on any of the above (1)–(5) elements, such as the technological element for instance, then the work system becomes imbalanced due to the neglect of other critical components. The second aspect of balance recognises that financial constraints, job task limitations, customer demands, or expectations may limit the possibility of achieving a perfectly balanced system. In such cases, positive features in one element can help compensate for negative aspects in others that cannot be changed.

Balance Theory also points to the need to consider the organisation as a constellation of interconnected work systems. A balanced organisation is one that takes into account financial goals, human outcomes, and the positive and negative aspects of work system design, while striving to minimise negative outcomes for both employees and the organisation. This resonates with broader sociotechnical insights that emphasise the mutual adaptation of social and technical subsystems within larger organisational contexts (Baxter & Sommerville, 2011).

At the same time, the wide scope of Balance Theory poses a challenge. Because it encompasses many dimensions of work and organisation, it risks becoming overly inclusive and losing analytical precision. In this thesis, balance theory is therefore not used as a predictive model, but as a *sensitising theory*. It helps to structure empirical observations and to guide attention to how changes introduced by autonomous systems give rise to shifts across different dimensions of the work system. This makes it possible to highlight important but sometimes overlooked aspects of organisational change, without presupposing simple causal relationships between system elements.

This theory is further developed by Carayon et al. (2015), who introduce a multi-level theory for understanding workplace safety within sociotechnical systems. Their model highlights the importance of considering not only the immediate work system, but also its interactions with broader organisational structures and the external environment. This layered approach reinforces the idea that organisational outcomes emerge from the dynamic interplay between system elements at multiple levels. It provides a way of situating the local effects of autonomous systems within a broader constellation of organisational and environmental factors, which is crucial for understanding how autonomous systems reshape work in practice.

3.2.4 Summary of Implications

Taken together, the three aspects of Sociotechnical Systems Theory provide a set of analytical tools for understanding how autonomous systems are designed, developed and implemented in mining. The principle of joint optimisation highlights the need to examine automation logics in terms of how they prioritise or balance social and technical subsystems. The operator perspective draws attention to the risk of marginalisation and the vulnerabilities that follow when human roles are treated as residual, rather than as integral to the functioning of sociotechnical systems. Finally, the multilevel perspective shows that the implications of autonomous systems are not confined to immediate operator–machine interaction, but reverberate across organisations and their wider environments. In this way, Sociotechnical Systems Theory provides a broad but valuable theory for analysing autonomous mining systems.

3.3 Communities of Practice

While Sociotechnical Systems Theory provides a broad theory for understanding the interplay between social and technical subsystems, it remains relatively general and is less suited to capturing the more fine-grained social processes that occur during implementation. This creates the need for a complementary perspective that can account more closely for how operator roles and practices are reshaped in the everyday processes through which autonomous systems are introduced and enacted, and for understanding what happens in the implementation of autonomous mining systems.

In Section 3.1.3, I outlined a primarily technical understanding of autonomous systems: not simply "more automation," but the integration of multiple technical components into a coordinated whole. This account highlights how autonomous systems differ from stand-alone automated functions by linking machines, software, and operators in more integrated and complex constellations. In the previous section on sociotechnical systems (Section 3.2), however, we opened the door to another layer of analysis. By drawing attention to the social subsystem, this perspective makes clear that beyond technical configuration lies a social and interpretive dimension, where social questions such as the meaning of autonomous technology become equally, if not more, significant.

Autonomous technology is not experienced as neutral but is charged with meaning, embodying both promises and uncertainties. On the one hand, it holds out prospects of improved efficiency, safety, and technological progress; on the other, it raises questions about consequences, scope, and implications for work, roles, and employment. This dual character makes their implementation particularly significant to examine, not least because such technologies do not spread by themselves. They are introduced, adapted, and sustained by people, who in the process interpret and give them meaning in everyday practice. Understanding this dynamic requires an analytical approach that can account for how people collectively engage with the technology, negotiate its significance, and reshape their roles in relation to it.

While Sociotechnical Systems Theory highlights the importance of the social subsystem, it offers little detail on the processes through which people learn, participate, and make sense of new technologies in practice. To capture these dynamics, I draw on the theory of Communities of Practice, which conceives of learning as a situated and social process.

The term "community of practice" gained traction in the early 1990s through two partly independent contributions. Brown and Duguid (1991) examined how informal communities supported organisational learning and innovation, highlighting the importance of social interaction for knowledge sharing. Around the same time, Lave and Wenger (1991) introduced the concept in their work on situated learning, focusing on apprenticeship and the idea of legitimate peripheral participation as a way of understanding how learning is embedded in practice. Both strands challenged dominant cognitive theories at the time, instead emphasising that learning is socially situated and develops through participation in everyday activities (Cox, 2005; Gherardi, 2009).[22]

Since its introduction, the concept of "communities of practice" has been further developed and reinterpreted. In later work, E. Wenger, McDermott, and Snyder (2002) moved from a descriptive account of learning in practice to a more prescriptive orientation, presenting communities of practice as a managerial tool for fostering knowledge sharing and organisational development. This shift has generated debate: some argue it creates conceptual ambiguity, while others view it as a strength that has allowed the theory to be adapted and reused across a wide variety of fields (Cox, 2005). More

[22]For an overview of the theoretical assumptions and trajectories of these early works, see Cox (2005) and Gherardi (2009).

broadly, the concept has been taken up in diverse and sometimes inconsistent ways across disciplines, which has given rise to both ambiguity and a tendency towards normative appropriation in managerial discourse (Cox, 2005; Gherardi, 2009).

In this thesis, I focus on the account presented in (É. Wenger, 2008), titled *Communities of Practice: Learning, Meaning, and Identity*, which understands a community of practice as a group of people who share a concern or passion for something they do, and who learn how to do it better through regular interaction. This theory of learning takes neither the individual nor the social institution as its primary unit of analysis (É. Wenger, 2008). Instead, it emphasises the informal communities that people form and participate in as they pursue a shared enterprise over time. The theory explores themes such as community, social practice, meaning, and identity, and is organised around three interrelated dimensions (É. Wenger, 2008):

1. *Mutual Engagement* – the relationships of mutual engagement that bind members into a social entity. Mutual engagement concerns how the community of practice functions.

2. *Joint Enterprise* – the collective endeavour as understood and continually renegotiated by the members. It refers to what the community of practice is fundamentally about.

3. *Shared Repertoire* – the shared repertoire of communal resources (routines, sensibilities, artefacts, vocabulary, style, etc.) that members have developed over time. Shared repertoire concerns the capabilities the community of practice has produced.

These three dimensions are not intended as rigid categories, but as analytical lenses that can help illuminate how social learning and participation take shape in practice. In the following subsections, I discuss each of them in greater depth and show how they inform the analysis of the implementation of autonomous mining systems in this thesis. More broadly, communities of practice theory provides a conceptual foundation for understanding how the introduction of new technology reshapes roles, competences, and everyday practices in organisations.

3.3.1 Reconfiguring Relations through Mutual Engagement

The implementation of autonomous systems unavoidably transforms relations of work, raising the question of who gains a central role in the new practice and who risks being sidelined. A central dimension in the dynamics that underlie this process is what É. Wenger (2008, 73-77) terms *mutual* *engagement*. This refers to the ongoing interactions through which participants build relationships, negotiate meaning, and sustain a shared practice. Mutual engagement cannot be captured by formal job descriptions or organisational structures. Instead, it is constituted in the encounters where people rely on one another, develop trust, and coordinate their activities in ways that bind them into a social entity. In Wenger's words, practice "does not exist in the abstract" (É. Wenger, 2008, 73), but emerges through these patterns of engagement in everyday work. As he illustrates with the example of insurance claims processors, it is not their formal co-location in an office or their contractual job titles that make them a community of practice, but the dense relations of collaboration and interdependence that they sustain around the shared activity of processing claims (É. Wenger, 2008).

From an analytical perspective, mutual engagement highlights that the coherence of a practice depends on the quality of relationships and the ways in which members recognise each other as participants. Importantly, this is not given in advance but is accomplished through interaction: who is included, whose knowledge is taken into account, and whose contributions are recognised are all matters negotiated in practice. As such, mutual engagement provides a way of analysing the dynamics of inclusion and exclusion, and how some actors become central while others risk being left in the periphery.

In the context of implementing autonomous mining systems, this dimension is particularly relevant. New technologies reshape existing work practices, redistribute responsibilities, and require new forms of collaboration across roles. Whether operators, engineers, or supervisors are able to engage mutually with one another, and on what terms, becomes crucial for how the technology is enacted and sustained in everyday work. The concept of mutual engagement therefore directs analytical attention to the relational work through which communities form, adapt, and maintain themselves in the midst of technological change. In this thesis, the concept of mutual engagement is used to highlight how participation is structured, how relations of interdependence are built or disrupted, and how roles are reconfigured during the implementation of autonomous systems.

3.3.2 Negotiating Meaning through Joint Enterprise

The introduction of autonomous systems is accompanied by multiple and sometimes competing understandings of what the technology represents. As noted in Section 2.3 and discussed further in Paper IV, the motivations for adopting such systems are diverse: increasing efficiency, reducing production costs, minimising human error, and improving safety. Each of these drivers carries with it a particular promise of what the technology is supposed to deliver – whether relieving workers of monotonous tasks, improving operational reliability, or signalling technological progress. At the same time, before implementation these promises remain somewhat indeterminate, and the technology itself represents something unknown, even ambiguous, within the organisation. Autonomous systems can therefore be understood differently depending on one's standpoint: for management, they may embody strategic investment and competitiveness, while for operators they may raise questions about job security, role change, or altered work practices. As shown in Paper III, the understanding of autonomous mining systems is not uniform but subject to variation across organisational levels and perspectives.

The analytical challenge, then, is to understand how these different interpretations are brought together into a shared orientation that enables collective action. How does a technology that carries heterogeneous and sometimes contradictory promises come to be defined and understood as something that people can act upon together? This is where Wenger's concept of "joint enterprise" becomes particularly relevant.

According to É. Wenger (2008, 77–81), a joint enterprise is not simply a stated organisational goal or a pre-defined objective. It emerges through the ongoing process of negotiation among participants, reflecting their responses to shared conditions. In this sense, a joint enterprise is both enabling and constraining: it creates relations of accountability that specify what matters, what actions are legitimate, and how responsibilities are distributed within a practice. Crucially, it is not a static consensus but an evolving and contested construction, defined by those who pursue it together. Disagreement, resistance, and ambivalence are not anomalies but integral to the process, as members work out what the enterprise is about and how it should be carried forward.

To illustrate the concept of joint enterprise, we can return to the example of insurance claims processors discussed by É. Wenger (2008, 77–80). Their enterprise was never limited to the formal task of handling claims on behalf of the company. While this organisational demand framed their work, what the practice was really about emerged through their own negotiations: earning a living, coping with monotony, sustaining a sense of self, and making the workplace habitable. In this sense, their joint enterprise reflected not just compliance with external objectives, but a collectively constructed response to their situation. The example underscores that a joint enterprise is not reducible to stated goals, but is defined by participants as they pursue it together.

From this perspective, joint enterprise provides a lens for analysing how the meaning of autonomous systems is collectively negotiated within organisations. It directs attention to how participants articulate purposes, align expectations, and establish forms of accountability that make the technology intelligible and actionable despite its initial ambiguity. In this thesis, the concept of "joint enterprise" is used to highlight how diverse understandings of autonomous mining systems are transformed into a shared project that both reflects and reshapes organisational life during implementation.

3.3.3 Establishing a Shared Repertoire

Autonomous technology, by virtue of its systemic character, rarely arrives as isolated functions or single machines. As discussed earlier, such systems typically involve the integration of multiple components and thus entail substantial investments. These investments, in turn, require more than the mere installation of equipment: they call for the establishment of new routines, the redefinition of roles, and the coordination of practices that allow the technology to become workable in everyday organisational life. In this sense, the challenge of implementation lies in how the technology becomes anchored in the social fabric of the organisation – through the creation of practices, languages, and tools that allow it to be used, understood, and maintained.

Wenger describes this dimension of practice as the development of a shared repertoire (É. Wenger, 2008, 82–84). Over time, communities of practice generate a set of resources for negotiating meaning: routines, concepts, symbols, tools, stories, or even jokes that crystallise from collective experience. These elements are not static; they reflect histories of engagement yet remain open to reinterpretation in new situations. In this way, a shared repertoire provides both continuity and flexibility, sustaining practice while enabling it to adapt. Importantly, it encompasses both formal and informal elements – codified procedures and tacit know-how, technical artefacts and social rituals – that together form the building blocks of a community's capacity to act.

For example, Wenger notes how communities may incorporate artefacts, stories, or even bits of workplace gossip into their repertoire, blurring the line between formal and informal resources (É. Wenger, 2008). Such elements may appear peripheral, yet they can be crucial for sustaining participation, conveying shared understandings, and maintaining coherence within the community. In this sense, a repertoire is as much about interpretive resources as about technical ones: it provides members with ways of saying, doing, and showing what matters in their practice.

In this thesis, the concept of shared repertoire is used to highlight how the implementation of autonomous systems depends on the creation of new routines, terminologies, and practical arrangements. It directs attention to the concrete resources – both technical and social – through which the technology is enacted, institutionalised, and made meaningful in everyday mining practice.

3.3.4 Summary and Implications

The theory of Communities of Practice provides an important complement to Sociotechnical Systems Theory. While the latter offers breadth by positioning technology within broader organisational and social arrangements, Communities of Practice adds depth by foregrounding the dynamics of learning, participation, and meaning-making in implementation. It highlights how practices take shape through mutual engagement, how purposes and accountabilities are negotiated as a joint enterprise, and how repertoires of routines, tools, and shared understandings sustain collective activity over time.

In this thesis, the theory is used as an analytical lens to examine how the introduction of autonomous systems reshapes roles, competences, and everyday practices. It draws attention to the processes through which technology acquires meaning, becomes workable in practice, and is integrated into organisational life. In doing so, Communities of Practice provides a foundation for analysing how implementation unfolds as a social as much as a technical process.

4 Methodology

This chapter outlines the overall research design, introduces the empirical studies and their data, and discusses the analytical strategies, research quality, ethical considerations, and philosophical positioning that guide the work. Together, these elements form the basis for understanding how the thesis approaches autonomous systems as a sociotechnical phenomenon explored through interpretive methods.

4.1 Overview of Thesis, Studies, and Projects

The research was conducted between 2019 and 2025 and follows the ongoing diffusion of autonomous and data-driven technologies in European mining, with empirical examples drawn from the Swedish mining industry – a period marked by intensified development and implementation efforts. Within this context, the thesis examines how such technologies are designed, developed, and implemented in practice, and how they reshape work and organisation.

The work adopts a qualitative and interpretive approach, combining different methods and sources to capture these processes as they unfolded. It builds on three interrelated studies, each situated within its own methodological and analytical context: a scoping literature review, a focus group study with technology developers, and an in-depth case study of an autonomous haulage system at a Swedish mine. In addition, a set of field notes was collected throughout the research process, documenting developments in the sector and reflections from fieldwork. Together, these studies represent a set of strategic entry points into the study of the ongoing transformation of mining work through autonomous systems.

4.1.1 Overview of Studies

The studies are summarised below and described in more detail in later sections of this chapter.

Table 4.1: Overview of empirical material by study, including project, method, sampling, data characteristics, analytical approach, and associated articles

Project	Study & method	Data source(s)	Sampling / Selection	Time frame	Data description	Analytical approach	Related paper(s)
Swedish project	Study I – Literature review	24 peer-reviewed articles from Scopus	Search strategy guided by PEO framework	Oct 2022	Thematic summaries across four categories	Thematic analysis, mapping and identification of research gaps	Paper I
EU project	Study II – Focus group study	5 expert group interviews with designers and developers	Purposeful convenience sampling via WP leaders in EU project	Dec 2021 – Feb 2022	Structured discussions on operator roles, safety, interaction, and trust, with participants from multiple European countries	Thematic analysis of focus group summaries	Paper II
Swedish project	Study III – Case study	24 interviews, notes, internal documents	Availability and convenience sampling during site visits	Mar 2023 – Jun 2024	Interviews, field observations, and internal documents from an open-pit mine in northern Sweden	Directed content analysis Thematic analysis	Paper III Paper IV
Thesis		Mining conferences and events	Availability and convenience sampling	May 2021 – Sep 2025	70 field notes amounting to about 30,000 words	Contextual understanding	Thesis

STUDY I — A scoping literature review aimed at mapping existing research on digitalisation and automation in the mining industry. The review included 24 peer-reviewed journal articles, selected through systematic searches in the Scopus database. The analysis focused on identifying common themes, trends, and knowledge gaps related to the work environment, organisational change, and technological development in mining.

STUDY II — A focus group study involving designers and developers of autonomous mining technology. The aim of the focus groups was to examine how developers understood and articulated the role of humans in relation to the autonomous technologies under development. Five sessions were conducted, each with approximately six participants, and included structured discussions, design scenarios, and reflective exercises. Notes and summaries from these group discussions formed the empirical basis for analysis.

STUDY III — A case study on the implementation of an autonomous haulage system (AHS) at a mine site in northern Sweden. The AHS consisted of a fleet of self-driving trucks operating within a designated area of the open-pit mine, coordinated primarily by control-room operators with support from on-site operators. The implementation of this system was managed by the mining company. The case study drew on 24 semi-structured interviews with operators, managers, and project personnel, as well as internal project documents and field notes from meetings, events, and site visits.

Each study drew on distinct types of qualitative data. Table 4.1 provides a comprehensive overview of the empirical material underpinning the thesis, including data sources, methods, sampling strategies, analytical approaches, and how each study connects to the appended papers.

Taken together, the three studies represent a set of strategic empirical entry points into how autonomous systems are designed, developed, implemented, and how they reshape operator work. Rather than following a linear progression, the studies provide complementary perspectives on different phases of this process: STUDY I mapped existing research and identified knowledge gaps; STUDY II examined how designers and developers conceptualise operator roles, illuminating the logics of design and development of autonomous mining systems; and STUDY III followed the implementation of an autonomous haulage system, analysing how autonomous mining technology becomes integrated into organisations and everyday work practices.

Shaped by two large-scale research projects (described below), this combination of studies reflects a deliberate ambition to capture the phenomenon from multiple vantage points. Taken together, these studies provide partial but complementary perspectives that, in combination, offer insight into central dynamics through which autonomous mining systems are shaped, realised, and made meaningful in practice. The overall research design is abductive and iterative, drawing on diverse empirical materials and theoretical frameworks to develop the understanding of how autonomous mining systems reshape work in mining.

4.1.2 Summary of Projects

These studies were conducted within the framework of two large-scale research projects, which are briefly described below.

The Swedish Project

The aim of this project was to develop a roadmap for safe, inclusive, and attractive mining work. Conducted between 2022 and 2025, it was led and coordinated by the Work Science division at Luleå University of Technology (LTU), in collaboration with Sweden's two largest mining companies and a company specialising in transport and contracting solutions for the mining industry. The project was multidisciplinary and involved several researchers and company representatives, addressing a broad range of themes including safety, gender, technology, competence, and the green transition. My contribution focused on technology development and the future of work. The research conducted within this project formed part of Study I and Study III, described previously, and provided the empirical basis for Paper I, Paper III, and Paper IV.

The EU Project

This project, conducted between 2021 and 2024, was part of a large-scale European research collaboration aimed at developing new concepts, technologies, and practices for the future of sustainable and intelligent mining systems. The project brought together mining companies, equipment manufacturers, technology developers, and universities around a shared vision of a carbon-neutral, safe, and efficient mining operation driven by automation, electrification, and digitalisation. The project was technologically intensive and addressed a wide range of themes, including robotics, connectivity, underground infrastructure, and human–machine interaction. My contribution was situated within the work on the "digital miner," and focused on technology development and the future of work. The research conducted within this project formed the basis for Study II and Paper II.

4.2 Studies and Data Collection Methods

This section presents the data collection methods used in this thesis, structured around the three empirical studies (Study I–III). Rather than treating methods in isolation, each subsection combines a more detailed account of each study with a description of the specific data sources, techniques, and procedures used. This integrated format allows for a presentation of how empirical material was generated in each study and in relation to each research setting, focus, and design. See Table 4.1 for an overview of the empirical material, including methods, data sources, sampling strategies, time frames, analytical approaches, and how each dataset connects to the appended papers.

4.2.1 Study I – Scoping Literature Review Study

The first study, published as Paper I, was conducted in collaboration with Annika Pekkari, Jan Johansson, and Joel Lööw within the Swedish research project (see Section 4.1.2) on safe, inclusive, and attractive mining work. A scoping literature review design was chosen because the research field of digitalisation and autonomous technologies in the mining industry is both emergent and heterogeneous, making it more important to map existing knowledge and gaps than to synthesise findings into definitive conclusions. Scoping reviews are particularly well suited for such purposes, as they provide a systematic yet flexible approach to mapping the breadth and nature of existing research, clarifying key concepts, and identifying gaps that warrant further empirical study (Arksey & O'Malley, 2005; Levac, Colquhoun, & O'Brien, 2010). This methodological choice supported the thesis in two ways: first, by establishing an overview of how digitalisation and automation in mining have been studied in relation to work, organisation, competence, and society; and second, by highlighting the conceptual and empirical blind spots that motivated and guided the design of the subsequent empirical studies.

The search strategy was constructed using the PEO framework (Population–Exposure–Outcome), which is a systematic approach for developing transparent and reproducible search strings. In this study, the population was defined as the mining industry, the exposure as digitalisation and automation technologies, and the outcomes as implications for work, organisation, and competence. Table 4.2 shows how these elements were operationalised into search terms.

Table 4.2: Operationalisation of the PEO framework and search terms

PEO element	Concept	Search terms
Population	Mining industry	`mining industr*`, `mining compan*`
Exposure	Digitalisation and automation technologies	`"industry 4.0"`, `"industry 5.0"`, `digitali?ation`, `automation`
Outcome	Work and organisational effects	`competenc*`, `skill*`, `abilit*`, `aptitud*`, `"work environment"`, `"work organi?ation"`, `ergonomic`, `"human factors"`

The material was screened in two stages. First, titles and abstracts were assessed against the review purpose. Publications not written in English or Swedish, those outside the mining industry, and those exclusively focused on coal mining, were excluded. In a second stage, articles that addressed technology without any consideration of work environment, organisation, or competence were also excluded. This process resulted in 24 included publications. These were distributed among the authors, summarised, and then categorised into four themes: work environment, competences, organisation, and society. The thematic structure was not only a pragmatic way of organising the literature but also reflected the broader concerns of the thesis – namely, how digital and autonomous technologies intersect with conditions of work, organisational change, and societal impact.

The review highlighted both the promises – such as improved safety, potential for more attractive workplaces, and efficiency gains – and the limitations of existing research on digitalisation and autonomous technologies in mining, notably the lack of empirical evidence on how these technologies affect the quality and organisation of operator work.

While several studies describe technological opportunities and safety benefits, the review found few empirical investigations of how these technologies actually affect operator work in practice. Questions of work quality, organisational learning, and long-term competence provision were particularly underexplored, despite broad consensus that digitalisation and automation will dramatically reshape mining work. These gaps were critical for the design of the subsequent studies in this thesis: the focus groups (Study II) were motivated by the lack of research on how developers conceptualise the human role in autonomous technologies, while the case study (Study III) addressed the need for analyses of implementation processes and their implications for operators. More broadly, the review showed that technological change cannot be understood in isolation from social and organisational dimensions, a conclusion that directly underpins the thesis's focus on how autonomous systems reshape operator work. In this way, the scoping review did not merely survey the literature but provided a strategic entry point that justified the empirical trajectory of the thesis.

4.2.2 Study II – Focus Group Study

Building on these insights, the second study (Study II) was conducted in collaboration with Joel Lööw and Jan Johansson. The study turned to the perspectives of technology developers themselves. While the review pointed to a lack of empirical research on how human roles are conceptualised in the design of autonomous technologies, the focus groups provided an opportunity to explore this dimension more directly.

Research context and purpose

To investigate how designers and developers working with mining technologies conceptualise the role of operators in relation to autonomous systems, a focus group study was conducted. The study was carried out within the EU project described earlier (see Section 4.1.2). The purpose was to explore assumptions about operator–technology interaction, safety, trust, and required competences, thereby providing insight into how human roles are imagined in the design and development of autonomous mining technologies. The study formed the empirical basis for Paper II.

Methodological rationale

Focus groups were chosen because they enable collaborative exploration of future-oriented questions and are well-suited to eliciting assumptions, expectations, and knowledge among experts (Krueger & Casey, 2015). Unlike individual interviews, focus groups allow participants to reflect upon and challenge each other's perspectives, which often brings implicit assumptions to the surface. In this study, the format had the unanticipated effect of encouraging participants to move beyond the immediate concerns of their daily work and engage with broader questions about trust in technology, the relationship between the systems they design and human operators, and the competences needed to support these interactions. This dynamic emerged through the collective setting, which fostered a level of engagement and interest that may not have occurred to the same extent in individual interviews, highlighting the value of focus groups for eliciting shared reflections on themes that are not always addressed explicitly in participants' professional practice.

Participants and sampling

The participants were drawn from the EU mining project (see Section 4.1.2) and included individuals involved in the design and development of autonomous mining technologies. While their roles varied, some being directly engaged as designers and developers, others contributed in a more indirect or overarching capacity at the project level. For the purposes of this study, however, all informants were conceptualised as designers and developers in order to capture their shared involvement in shaping the technologies under discussion. They were also considered experts in their field, in line with Flick's definition of expert interviews (2018), as they brought specialised knowledge of designing and developing autonomous mining solutions – knowledge beyond everyday experience that was central here, since the study sought their professional expertise primarily.

Sampling was handled in collaboration with work package leaders in the EU project, who were first invited themselves and also asked to recruit additional participants from their organisations. The main selection criterion was that participants should have relevant expertise or experience enabling them to contribute meaningfully to the focus group discussions. This process combined purposive and convenience sampling: participants were selected based both on their expected ability to provide valuable input and on their accessibility within the project's structure.

A total of 27 individuals participated across the five focus group sessions. Some attended more than one session, but the majority participated only once. The participants represented a range of organisations, including OEMs, mining companies, and research institutions, and were based primarily in Sweden, Finland, and Germany. The gender distribution was skewed, with the majority of participants being male; four of the participants were women. While individual backgrounds varied, all participants were professionally engaged in the development of autonomous mining technologies.

Data collection

The focus groups were organised according to the project's focus areas (see Table 4.3). Out of ten possible focus areas, five were selected for the study. The selection excluded areas with minimal operator interaction (e.g. rock stress monitoring and sustainable mine design) in order to maintain relevance to the research purpose.

Table 4.3: Focus groups by focus area in the EU project

Focus area	Title
1	Connectivity and positioning
2	AI powered fleet optimisation
3	Robotised inspection
4	Autonomous material handling
5	Autonomous vehicles in mixed traffic

Five semi-structured focus groups were conducted by me in collaboration with Joel Lööw. Each session lasted approximately two hours with a short break, except for one smaller session with two participants that lasted one hour. Most focus groups included participants from different organisations, except the smaller session where both came from the same company. Two sessions were conducted in Swedish, and three in English. All sessions were held online via Microsoft Teams.

An interview guide was used to structure the sessions, but it was not followed strictly. In line with Krueger and Casey's recommendations (2015), thematic direction was guided by participant responses, with follow-up questions and probes used to add depth. The discussions focused on what the technologies under development were intended to do, and what operators would need to understand and manage in order to work effectively with them. Particular emphasis was placed on safety, trust, and operator–system interaction. The questions assumed that the technologies would eventually be implemented, although this was speculative in practice.

Analysis

During the focus group sessions, I was primarily responsible for posing questions and follow-ups, while Lööw took extensive notes. I also took general notes, and Lööw occasionally asked questions. Shortly after each session, we independently wrote up our notes and then compared them to identify any gaps. Lööw subsequently compiled and rewrote the notes into summaries, which captured the overall content of each focus group session without attributing statements to individuals. The summaries were sent to participants for review and feedback, and only minor clarifications were made.

The final data corpus consisted of anonymised summaries of each focus group session, providing a composite view of expert perspective on operator roles in autonomous mining systems. The data were thematically analysed in collaboration with Lööw and Jan Johansson, through repeated readings and comparative interpretation across the summaries. I had the main responsibility for writing the paper and leading the analytical work.

4.2.3 Study III – Case Study

Whereas the focus group study (Study II) examined how developers and designers envisioned the human role in autonomous technologies during the design phase, the third study moves closer to the lived realities of technological change. Here, the focus deepens: attention shifts to the implementation stage – the point at which autonomous systems encounter the practical, organisational, and social complexities of mining work. The study explores how these systems are introduced, adapted, and made workable in everyday practice, and how this process reconfigures operator work and reshapes the organisational fabric of mining.

Research context and purpose

To investigate the implementation of autonomous systems in mining and how they reshape operator work, a case study was conducted on the introduction of an AHS in an open-pit mine in northern Sweden. The aim was to gain insights into how autonomous mining systems are implemented within mining companies and how these systems affect the work of operators. The study was conducted within the Swedish research project described earlier (see Section 4.1.2).

During one of the project's conferences for the Swedish project, a participant presented the AHS implementation project, which at that time was still in its early stages. This presentation drew my attention and led to the idea of conducting a case study of the implementation. The decision was therefore both a practical opportunity made possible by my involvement in the Swedish project, and a deliberate methodological choice to investigate the phenomenon in its organisational context.

The case study approach was chosen because it enables in-depth examination of a phenomenon within its real-world setting (Yin, 2018). This makes it particularly well-suited for studying implementation processes, where the dynamics between technology, organisation, and work practices can only be understood in situ.

The Case Study: Research design

In methodological terms, "the case study" refers to the mode of inquiry adopted to investigate a bounded case in depth and within its real-world context (Yin, 2018). While "the case" points to the specific empirical instance – in this thesis, the implementation of an autonomous haulage system – the case study refers to the research design, data collection, and analysis used to examine that instance. This distinction is important for clarity, as the case study is intended not only to understand the particular case but also to generate insights that may inform our understanding of similar situations.

The study was designed as an exploratory single-case study (Yin, 2018), aiming to generate an in-depth understanding of the implementation process in a specific organisational setting. The exploratory character reflects the focus on capturing how the project unfolded in practice and identifying themes and patterns, rather than testing predefined hypotheses. To support this, a case study protocol was developed at the outset, outlining the purpose, scope, and methods of the study. The protocol was iteratively updated as the research progressed, providing a systematic structure while allowing flexibility as new insights emerged.

The rationale for selecting this case was twofold. First, the project represented the first implementation of this autonomous haulage system in Sweden and Europe, offering a unique opportunity to examine how such technologies are introduced and integrated into organisational practice in this context. It therefore provided an illustrative example of how the future of working life in mining may be shaped by autonomous technologies. Second, the opportunity to study the case emerged through my participation in the broader Swedish research project (see Section 4.1.2). This collaborative setting enabled access that would otherwise have been very difficult to secure, including permission to conduct site visits, interviews, and observations. Access was thus not simply a matter of convenience but a condition for conducting in-depth empirical research in an industrial context that is often closed to external researchers.

The implementation project was carried out exclusively by the mining company, with a dedicated project group leading the process from initial preparations to the eventual handover to production. It formally began in October 2021 with planning activities, followed by infrastructure work, security classification, and the installation of hardware and software. These early stages were mainly driven by project leaders and technical specialists, with little direct involvement from operators and limited opportunities to observe more than planning and installation work. By early 2023, the project had reached a stage where the first autonomous trucks were being tested and validated on site. This was also the point at which this case study started. At this time, around four operators were present, and implementation activities had advanced to a level where day-to-day work practices began to take shape. What had previously been abstract plans and preparations now turned into practical trials of the system, creating opportunities to study both technical adjustments and the gradual emergence of new operator roles. The fact that the study did not cover the initial stages of the project is not necessarily a limitation. The Swedish research project (see Section 4.1.2) started later, which meant that I was neither aware of nor had access to the implementation during its earliest phases. In many ways, however, beginning the study once the system was being tested was advantageous. It allowed me to focus on the point when the technology became tangible in practice and when the involvement of operators increased. A possible drawback is that my understanding of the preparatory stages relies on company documents and retrospective accounts, rather than direct observation. Still, for the purposes of examining how the technology was put into use and how operator work evolved, this timing offered the most relevant starting point.

The Case: Implementation of AHS

The term "case" refers to the unit of inquiry, that is, a specific instance of the phenomenon under investigation (Yin, 2018). In this study, the case is the implementation of an AHS at a mining site in northern Sweden.

The AHS is designed for transporting materials using self-driving trucks, which are integrated into a fleet management software system. This enables coordination between trucks and other machines in the production area to optimise haulage routes, maintain flow, and minimise disturbances. The autonomous zone is enclosed with barriers and gates, allowing only vehicles equipped with the system to enter – including operator vehicles, maintenance trucks, excavators, and other relevant machinery. The system is supervised from a control room located outside the mine, where operators monitor a two-dimensional, bird's-eye view of the fleet. Their work is supported by on-site operators inside the autonomous zone, who handle disturbances and provide situational interpretation of the physical environment.

On one level, the case is defined by its particularity: the project was the first Swedish and European implementation of this specific system, carried out by a single mining company in collaboration with its technology supplier. It represents the local process of introducing, testing, and integrating autonomous haulage into ongoing mining operations.

On another level, the case can also be understood as an instance of a broader phenomenon. It exemplifies how the introduction of autonomous production systems reshapes work in practice, involving both technological adjustments and the reconfiguration of roles, responsibilities, and organisational arrangements. In this sense, the case is not only about one company or one project, but about the wider transformation of working life in mining as autonomous technologies become part of everyday operations.

Data collection

Data collection for the case study drew on three sources: interviews, observations, and project documentation. Among these, interviews formed the primary data source and are described in detail in the following subsection. Observations and documents, however, also played an important role in contextualising and deepening the analysis.

Observations. Through my participation in the Swedish research project, I was given the opportunity to collect observational data alongside other forms of material. Observations are a useful complement in case study research, as they provide insights into practices and interactions that may not be fully captured in interviews or documents (Yin, 2018). In this study, they included visits to the autonomous zone, where I accompanied on-site operators in their daily work, and observed loading, tipping at dumps, and tipping into the crusher – both from the outside and from within the crusher control room. I also visited the central AHS control room, where operators supervised the fleet, and the training facilities, where I was able to test the simulator and drive virtually among autonomous trucks.

After each observation, I wrote detailed notes about what I had seen, heard, and experienced. These notes formed part of my broader set of field notes, which also included documentation from conferences organised within the Swedish research project, where participants reflected on implementation themes from different perspectives. The field notes as a whole are discussed further in Section 4.2.4.

Documents. Documentary material was another important source of data. This included work descriptions, PowerPoint presentations given by project leaders, as well as internal and external news articles. Documents can provide valuable contextual information and serve as a means of corroborating evidence in case study research (Yin, 2018). In this study, the documents were primarily used to provide contextual understanding of the implementation process, while the work descriptions also formed part of the analytical material for Paper IV.

Interviews. Interviews served as the primary method of data collection within this case study, providing detailed insights into how the implementation process was experienced and managed by those directly involved with the technology. Interviews are a common and valuable source of evidence in case study research, as they provide access to participants' perspectives and interpretations of ongoing processes (Yin, 2018). At the same time, interviews should not be regarded as neutral accounts but as structured interactions shaped by the roles and positions of both interviewer and interviewee. As Kvale (2006) notes, interviews are not simply friendly dialogues but inherently asymmetrical encounters, where the interviewer has interpretive authority and control over the framing of questions and the direction of the conversation. This understanding informed my approach: while I aimed to elicit open accounts, I also reflected on my own role in shaping the material and the potential biases introduced by the interview situation.

To explore participants' experiences, the study employed a semi-structured interview design. The interviews focused on the perceived effects of the autonomous haulage system on work practices and organisational structures. This format was chosen because it allows for both consistency and flexibility: a set of key themes guided the interviews, but the structure remained open enough to follow up on issues raised by the participants themselves. In this way, the interviews were not limited to pre-defined categories but allowed for unanticipated topics to emerge, offering empirically rich accounts of the material (Yin, 2018).

Sampling for the interviews was based primarily on availability during different data collection occasions. Interviews were scheduled with personnel who were present (and willing to participate) on site during my visits. While this approach was somewhat constrained by logistical factors, the relatively small size of the team involved in the AHS implementation project meant that, by the end of the data collection period, most of the relevant individuals had been interviewed, some even twice. In particular, more than half of the on-site operators and control room operators working in the autonomous zone participated. Although selection was determined by practical circumstances, the resulting sample nonetheless captured a broad and representative range of perspectives from those directly involved in the implementation.

In total, 24 interviews were conducted across four separate data collection periods. An overview of the interviews and their duration is presented in Table 4.4. Each participant received an informed consent form outlining the purpose of the study, their right to decline to answer questions, their ability to withdraw at any point, assurances of confidentiality to the greatest extent possible, how the recordings would be handled, and my contact information.

Most on-site operator interviews (except for On-site Operator 1) were conducted in a parked car during field visits to the autonomous zone. Although the car was stationary, the informants remained attentive to ongoing activities and were required to respond to any radio calls. One interview was interrupted by a disturbance and could not be completed before the end of the shift. While this was unfortunate, it also offered a valuable first-hand observation of the kinds of disturbances that can occur within the system

Table 4.4: Overview of interviews

Role	March 2023	August 2023	May 2024	June 2024
On-site operator 1	22:13			
On-site operator 2		24:34*		40:52*
On-site operator 3			38:19*	
On-site operator 4				25:45*
Team Leader On-site operations	33:37	27:33		
Excavator operator			41:33	
Control-room operator 1	19:31		24:40	
Control-room operator 2			1:00:29	
Control-room operator 3			29:12	
Control-room operator 4			34:34	
Operations manager for control-room			44:58	
Program manager	39:21			
Section manager	35:50	39:22		
Safety coordinator		42:33		
Productivity leader		23:02		
Trainer 1	44:54	34:38		
Trainer 2		30:09		
Trainer and communicator		37:19		
Operations leader			47:19	

* Interviews marked with a star were conducted in a parked car during a field visit to the autonomous zone. One of these interviews was interrupted by a disturbance and could not be completed before the end of the shift.

and the type of operator work required to manage such situations. The remaining on-site operator interviews were conducted during periods without major interruptions, apart from occasional radio traffic. All informants also informed their colleagues in the control room that they were being interviewed and should not be disturbed unless necessary. All other interviews, including on-site Operator 1, were conducted in an office building located some distance from the mine site.

The interview guide was used as a reference but not followed rigidly. While it ensured that central themes were consistently addressed, its flexible application also allowed participants to shape the direction of the interview. This supported a more exploratory mode of inquiry and helped identify issues that were significant to the participants themselves. All interviews were recorded using a dictaphone. Twelve interviews were transcribed verbatim by me, while the remaining twelve were initially transcribed using an AI-based tool (klang.ai) and then carefully checked against the recordings.

Case Study Analysis

The conceptualisation of the case study followed the broad guidelines outlined by Yin (2018), who approaches case study research from a realist position, treating data as a relatively direct representation. At the same time, there are other traditions within the case study literature that emphasise more social constructivist perspectives, for instance by highlighting how cases are also co-constructed through narrative and interpretation (Dyer & Wilkins, 1991). While this thesis is primarily situated within a critical realist epistemological position (see Section 4.4.4), the analysis in PAPER III drew on directed content analysis and incorporated interpretive elements closer to the constructivist tradition, reflecting the collaborative character of the work with Magnus Nygren. PAPER IV, by contrast, was analysed by me alone using thematic analysis and adopts a more critical realist orientation. Both approaches are described in greater detail in Section 4.3.

Data analysis drew on multiple sources, including interviews, observations, and documents. The combination of these sources enabled data triangulation (Yin, 2018), which strengthened the robustness of the findings and contributed to a richer understanding of the phenomenon under investigation. At the same time, I remained aware of potential biases in the material and in my own position as researcher. Triangulation was therefore not only a matter of bringing together insights from different sources, but also a strategy for critically reflecting on how each form of data highlighted different aspects of the material. In addition, the collaborative analysis work with Magnus Nygren in PAPER III constituted a form of researcher triangulation, which further strengthened the interpretation of the material.

4.2.4 Field Notes

In addition to the three main studies described above, I have systematically collected field notes throughout the research process. These notes were not part of any single study, but served as a complementary source of insight across the thesis as a whole.

The field notes were generated through an ethnographically inspired approach to my involvement in the research setting, including mining conferences, site visits, demonstrations, and meetings with mining companies. I drew methodological inspiration from street phenomenology and the "go-along" method as an *in situ* approach to collecting qualitative data. This method combines elements of traditional phenomenological approaches, such as interviews and participant observation, enabling data collection through engagement and movement within natural environments (Kusenbach, 2003).

During interactions with actors such as researchers, engineers, developers, managers, and project partners from both the EU project and the Swedish project, I took notes in a variety of settings. Part of the field notes were collected within the scope of these two projects, during meetings, workshops, mine visits, and other project-related activities. And, part of the notes were collected at mining-specific conferences and industry events beyond the formal boundaries of these projects. At these events, I collected field notes related to themes that align with the core concerns of the thesis, such as the design and implementation of autonomous systems, operator experiences, and the changing nature of work. Many of these conferences were strongly technology-oriented, often focused on presenting specific technical solutions. In these settings, I took notes on the technologies presented while also reflecting on their potential effects on work and the broader consequences they may entail for operators.

At conferences and formal meetings, I sometimes typed notes directly on a computer. During mine visits, informal conversations, or technical demonstrations, I took handwritten notes, which I later transcribed. These notes also included casual observations and brief conversations in which I "asked around" in everyday spaces – such as coffee queues, elevators, or social gatherings – where relevant themes emerged spontaneously.

The approach is theoretically informed by Bourdieu (2008)'s concept of *field*, which refers to a structured social arena with its own rules, norms, and power relations, in which actors (individuals, groups, or institutions) occupy different positions depending on their power and capital. In practice, this meant viewing the mining industry landscape as a dynamic field in which multiple actors – from developers to end-users – negotiate meaning, influence, and direction through everyday interactions and decisions. While I have not focused specifically on the power relations between actors, my attention has been directed towards the joint process of designing and developing autonomous technology for mining – although power asymmetries between actors have, at times, been apparent.

While some of these notes, such as those written after site visits and operator observations within Study III, directly support the case study analysis, the general set of field notes described here extend beyond the case itself (discussed in Section 4.2.3). They cover a wider range of contexts, including project meetings, industry events, and informal interactions, and thus capture dimensions of the phenomenon that are not present in the case-specific material alone.

The field notes occupy an intermediate position in this thesis. They served both as documentation of events, conversations, and impressions encountered throughout the research process, and as a reflexive space for interpreting and making sense of these experiences. Although they were not formally coded or analysed, the notes informed the study by contributing to ongoing reflections, interpretations, and analytical decisions. They also became an important resource in the writing of the thesis, as I regularly returned to them to contextualise and refine the analyses.

The notes were not written according to any fixed format but followed a general ambition to record observations and reflections as the work progressed. In total, I collected approximately 70 notes, amounting to around 30,000 words. Each note was tagged and stored with searchable metadata, including date, title, and type. Their exploratory and open-ended character reflects the intention to remain attuned to the evolving research context. Rather than serving merely as background material, the field notes contributed actively to the analytical process and to the development of the qualitative analyses presented in the following chapters.

4.3 Data Analysis Methods

This section outlines the analytical strategies used in the thesis, focusing on two qualitative approaches: thematic analysis and directed content analysis. Thematic analysis was used in Paper I, Paper II, and Paper IV, and as the main method of analysis for the thesis, and directed content analysis was used in Paper III. While these approaches differ in how they relate to existing theory, they both involve systematic coding and interpretation of qualitative data.

Thematic analysis was conducted with the six-step process described by Braun and Clarke (2006), and can be used either to develop a rich, overarching account of the entire dataset or to explore a specific aspect in more depth (Braun & Clarke, 2006). Both strategies have been applied in different studies and papers. For example, the focus group study (Section 4.2.2) aimed to generate a broad understanding of the data, while the case study (Section 4.2.3) focused more narrowly on two different parts of the dataset for each paper.

In Paper I, II, and IV, the thematic analyses followed an inductive, data-driven approach, where themes were identified from the data without being constrained by predefined theoretical concepts. All analyses were conducted at the semantic level, focusing on what the participants explicitly said rather than interpreting latent meanings. In each case, the data were first coded manually or using NVivo, a software tool for qualitative coding and analysis, followed by thematic clustering and collaborative discussions with co-authors.

In the PaperIII, directed content analysis was used to examine the empirical material through a theory-informed lens. The analysis was based on the framework developed by Hsieh and Shannon (2005), in which existing theory guides the initial coding process. In this case, the analysis was structured around three core concepts from É. Wenger's theory of communities of practice: mutual engagement, joint enterprise, and shared repertoire (É. Wenger, 2008). Prior to coding, I discussed together with Magnus Nygren (who co-authored the paper) how these categories should be understood and applied in the context of the data. The interview transcripts were then divided equally among us, and coded using NVivo. During the coding process, collaborative meetings were held to discuss coding decisions and refine subcategories for each of the three theoretical themes. Some overlap in coding was also discussed to ensure consistency and shared interpretation. Citations from each theme were then selected and quoted during the writing process.

While thematic analysis allows for inductive, deductive, and abductive approaches, and directed content analysis typically begins from existing theory, both were applied here in an abductive mode; that is, an iterative movement between empirical material and theoretical frameworks, allowing both data and theory to inform the interpretation. This approach made it possible to generate insights while remaining open to refining or rethinking theoretical concepts in light of the empirical findings. This abductive strategy was central to the thesis's aim of producing theoretically informed insights into how autonomous systems reshape operator work and organisational dynamics.

4.4 Research Quality, Ethics, and Reflexivity

This section outlines the strategies used to ensure research quality and trustworthiness, the ethical principles and considerations guiding the studies, and the role of AI in the writing process. It also clarifies the philosophical positioning, highlights the importance of reflexivity and subjectivity, and acknowledges the limitations that frame the scope of the thesis.

4.4.1 Research Quality and Trustworthiness

Evaluating the quality of research based on qualitative data requires criteria that differ from those used in quantitative traditions. Rather than relying on concepts such as reliability, internal validity, or objectivity, this thesis draws on the trustworthiness concept developed by Lincoln and Guba (1986), as outlined by Flick in four categories (2018): credibility, transferability, dependability, and confirmability.

Credibility. Credibility – concerns the plausibility and trustworthiness of the findings. Credibility is viewed as the main criterion and refers to conducting research in ways that increase the believability, confidence, or perceived truthfulness of the findings. In this thesis, credibility was supported through prolonged engagement with the field, iterative data collection, and the use of theory-informed analysis strategies. For example, in the case study (described in Section 4.2.3), interviews were conducted across multiple visits, allowing for consistency, clarifications, and follow-ups on relevant themes. Collaborative data analysis with co-authors in several studies further strengthened the credibility of the interpretations by exposing them to multiple perspectives.

Transferability. Transferability – refers to the extent to which the findings can be applied to other contexts. While this thesis does not claim for generalisability in a statistical sense, transferability has been supported by providing thick contextual descriptions – particularly of the Swedish mining industry and the specific technological organisational setting of the implementation case. These descriptions allow readers to assess potential relevance of the findings to similar contexts.

Dependability. Dependability – relates to the stability of the research process over time. To enhance dependability, the studies were conducted using clear and documented procedures for data collection and analysis. Examples include the case study protocol developed for the case study, the systematic use of coding frameworks in Nvivo, and the consistent application of thematic analysis procedures across multiple studies.

Confirmability Confirmability – addresses the question of whether findings are grounded in the data rather than shaped by researcher bias. While the role of the researcher has been acknowledged (and will be further elaborated on in forthcoming Section 4.4.4), confirmability has been supported through strategies such as audit trails, transparent documentation of data collection and analysis processes, and data and researcher triangulation. For example, in the case study, data were contextualised with field observations and internal project documents, and in the focus group study (see Section 4.2.2), triangulation was made between co-authors to reduce individual interpretative bias, and the results were supported by participant feedback.

Together, these strategies aim to support the overall trustworthiness of the research by ensuring that the findings are both empirically grounded and transparently derived from the data.

4.4.2 Ethical Considerations

In this thesis, ethical considerations have been guided by both general research ethics principles and context-specific moral reflections. Alongside the practical strategies outlined above – such as informed consent, anonymisation, and reflexivity – the research process has been informed by the ethical guidelines set out in *God forskningssed* (Åkerman, 2024), which emphasise responsibilities such as truthfulness, transparency, integrity, and respect for participants. In line with Swedish law and the guidelines of the Swedish Ethical Review Authority (Görman, 2023), the projects and studies included in this thesis did not require formal ethical approval, as they did not involve sensitive personal data, physical intervention, or methods likely to cause psychological harm. Instead, participants were informed about the purpose of the research, their right to withdraw, and how data would be handled to ensure confidentiality and anonymity.

An underlying assumption in much of the discourse on automation and autonomous technology is that new technologies will improve working conditions by reducing physical risks. Previous research, including the scoping review in Paper I, confirms that safety can indeed be enhanced through autonomous systems. At the same time, as shown in later analyses (Paper III and Paper IV), the introduction of autonomous systems may also generate new psychosocial and organisational challenges. These tensions are addressed in the discussion chapter, but they are noted here as part of the broader ethical context in which the research was conducted.

From an ethical perspective, the balance of risks and benefits is important to consider. The technological changes that form the focus of this thesis were initiated and implemented independently of the research, and would have taken place regardless of whether they were studied. This means that the risks to participants arising from the research itself were limited, primarily involving the sharing of experiences and perspectives in interviews. By contrast, the potential benefits of the research lie in contributing knowledge about how autonomous systems affect work, work environment, and organisations. Given that the risks associated with participation were minimal, the study is considered ethically proportionate in relation to its anticipated value.

In terms of confidentiality and respect for participants, the strategies described for Study II–III (described in Section 4.2.2 and 4.2.3) were central. Informants were provided with information about the study's purpose and their rights, including the right to withdraw and the assurance of confidentiality. Given the relatively small and specialised nature of the mining industry, particular care was taken to avoid direct identification. This was addressed by anonymising names and roles, avoiding references to specific sites or projects when these could reveal identities, and presenting quotations in ways that protected individual participants.

Because access to the field in STUDY III was initially facilitated by gatekeepers, especially in relation to operators, issues of power asymmetry between employers and employees required attention. My experience, however, was that participants expressed a genuine interest in sharing their views on the new technology and spoke openly about both positive changes and challenges. Gatekeepers did not determine exactly who I interviewed, and once it became established within the groups that I was a researcher from LTU and what my project concerned, I was also able to recruit participants directly. All interviews were conducted during working hours, and particular care was taken to present the material in ways that ensured that critical or negative statements could not be traced back to individual participants.

In accordance with the General Data Protection Regulation (GDPR), the processing of personal data in this research was based on informed consent and on the university's mandate to conduct research in the public interest. No sensitive personal data, as defined by the regulation, were collected. The information associated with each interview was limited to participants' work role, approximate age, and gender. All raw data, including audio recordings, were stored securely on a password-protected computer to which only I had access. Identifying details such as names were not recorded. In line with LTU's guidelines for research data management, anonymised transcripts will be preserved for documentation and verification purposes, while the long-term storage or disposal of audio recordings will follow the university's archival and data protection procedures.

Ethical decisions were also relevant for how the research questions were formulated and what aspects of the phenomenon were explored. My own background, institutional position, and theoretical commitments inevitably shaped both the design and the focus of the research. Rather than treating these influences as neutral or incidental, I sought to acknowledge them and address their implications through ongoing reflexive practice. The research was also conducted within externally funded projects, which in part guided the broader themes to be studied and generated expectations regarding project deliverables. At the same time, I retained the freedom to develop the focus of the articles and the framing of the thesis in ways that reflected my own analytical interests. While the collaborative projects had their own objectives, the scientific analysis and conclusions presented in this thesis were carried out with full analytical independence.

Throughout the research process, I have aimed to remain ethically accountable not only by following established principles, but also by doing justice to the empirical material and the people who contributed to it. As

Flick (2018) notes, this includes grounding interpretations in data and being transparent about the analytical choices made. Doing justice to participants' contributions does not mean uncritically accepting everything they said; I also acknowledge that informants spoke from particular positions, with specific interests, and that their accounts were shaped by organisational roles, strategic concerns, and situational intentions. In this way, ethical research practice is understood not as a checklist, but as an ongoing responsibility embedded in each stage of the research process.

Taken together, the ethical considerations in this thesis have involved adhering to established principles, safeguarding confidentiality, being attentive to power relations, and engaging reflexively with my own role as a researcher. These different aspects are closely connected, and together they form the foundation for conducting the research in a manner that is both credible and fair to those who participated.

4.4.3 On the Use of AI

When I began working with this thesis, generative AI tools such as ChatGPT were not publicly available or widely used in academic writing. In the early stages of working with this thesis, including Paper I and Paper II, a professional language reviewer was hired to assist with improving grammar, clarity, structure, and coherence. These reviews were carried out after the papers had been drafted and focused specifically on enhancing the quality of academic language.

For the later stages of the work with this thesis – including Paper III, Paper IV, and the writing of this thesis – I made a strategic choice to use generative AI for similar purposes. This shift reflected both the increased accessibility of AI tools and a desire to integrate them into my own writing process. Rather than replacing writing, AI has functioned as a support tool, enabling more immediate, iterative feedback and encouraging a more reflective approach to academic communication. Throughout the writing process of this thesis, I have used ChatGPT as an assistant for text editing. This includes help with grammar, sentence structure, transitions, and clarity. My typical approach has been to send short sections of text – usually a paragraph at a time – to the model, asking for suggestions. I then compare the AI-generated suggestions with my original writing and decide what to accept, reject, or further revise. In this way, the use of AI has become a dialogical part of my writing workflow, prompting greater attention to structure, coherence, and phrasing.

In addition to text refinement, I have occasionally used AI to assist with other writing tasks, such as structuring sections of text, generating initial summaries of texts that I have written, or asking for feedback on specific formulations or transitions between paragraphs. In these cases, I use the tool to stimulate ideas or to test the clarity of my own reasoning.

I have approached the use of AI with caution, being aware of its potential risks, such that generative AI systems can produce inaccurate or biased content, and there are also concerns related to data security and the unintentional dissemination of unpublished material. To address these issues, I have used only a university-licensed version of ChatGPT, which ensures that the material processed through it is not stored or used for model training. My aim has never been to outsource intellectual work, but to enhance the communicative quality of the writing. This reflects a broader principle in academic publishing: that authors are responsible for any submitted material that includes the use of AI-assisted technologies and that authors must carefully review and edit any AI-generated suggestions, as such tools can produce text that appears authoritative but may in fact be inaccurate, incomplete, or biased. My use of AI has followed these principles. AI has served as a tool for improving expression and clarity, but the ideas, structure, and interpretations are the product of my research and critical engagement with the material.

4.4.4 A Note on Philosophical Positioning

Clarifying the philosophical underpinnings of a thesis is, I think, essential. It supports transparency, helps align the research purpose with the methodological choices made, and provides a foundation for both the analytical approach and the interpretation of the results.

I adopt a pragmatic critical realist epistemological position, which builds on Bhaskar's (2009) critical realism but leans towards methodological openness and practical engagement. Critical realism holds that reality exists independently of our knowledge of it, but also that our understanding of this reality is historically situated, shaped by conceptual frameworks, and always fallible. This combination of ontological realism, epistemic relativism, and judgement rationality – the idea that, despite this epistemic relativity, we can still make reasoned, evidence-based comparisons between competing explanations and judge some to be better than others – is central to Bhaskar's critical realism. These foundational assumptions align broadly with my research approach.

The pragmatic aspect of this position highlights the willingness to work across theoretical boundaries and draw on different kinds of knowledge, including interpretative and constructivist approaches, when doing so helps to generate meaningful explanations. Rather than treating philosophy as a rigid foundation for method, pragmatic critical realism supports a flexible, practice-oriented approach to inquiry (Price & Martin, 2018). As Archer

(2016) emphasises, critical realism is best seen not as a unified doctrine, but as a broad metatheoretical framework that can support diverse research strategies, including those oriented around social constructions of meaning-making and human action (Sayer, 2010).

The ontological commitment, that reality exists independently of our descriptions of it (Bhaskar, 2009), is a view that I am, on a good day, fairly optimistic towards. However, the more time I spend with questions of ontology, the less certain I become. I am more confident in, and therefore rely more strongly on, the epistemological tenets of critical realism. According to Bhaskar, the social and material world contains structures and mechanisms that operate regardless of whether we are aware of them. At the same time, the epistemological commitment maintains a strong relativism, acknowledging that our knowledge of this reality is always historically and contextually situated – shaped by the conceptual frameworks, social positions, and disciplinary traditions through which they are produced. Knowledge, in this view, is fallible, partial, and open for revision. Critical realism commits to developing the best possible explanations for observed phenomena – this is the principle of judgement rationality – given the available evidence and theoretical tools (Bhaskar, 2009). Research is therefore directed not only at describing patterns in the world, but at uncovering the underlying mechanisms and conditions that generate them.

While my overall epistemological position aligns primarily with critical realism, I consider this position compatible with social constructivist approaches from a pragmatic perspective. Pragmatic critical realism, inspired by Putnam's (1982) rejection of rigid fact-value distinctions and Gorski's (2013) emphasis on practical, experiential foundations of knowledge, provides the epistemological bridge necessary to integrate these positions. Putnam's critique of the rigid fact–value dichotomy helps dissolve the artificial boundary between objective explanations and value-laden interpretation. This supports the view that knowledge is always entangled with meaning and human concern – an assumption shared by interpretative and constructivist approaches, and one that can be integrated into a critical realist position. Gorski's focus on experience and practice foregrounds how knowledge is generated through social action – that is, how people experience and respond to real conditions. Together, these arguments support a research approach that treats meaning-making, values, and social practices as legitimate and necessary components of knowledge production – without giving up the possibility of reasoned comparison and empirical accountability.

This integration is particularly relevant throughout this thesis, where I draw on practice-oriented theories such as Wenger's (2008) communities of practice. Rather than seeing this as contradictory, I regard the emphasis on practice as complementary. Pragmatic critical realism accommodates practice-based, interpretative meaning-making, recognising that such practice occurs within – and interacts with – broader structures and contexts. From this perspective, social practices are essential for understanding how actors navigate and make sense of technological changes. Thus, pragmatic critical realism provides a productive synthesis, allowing me to integrate interpretive insights from social constructivist-inspired theoretical framework with the deeper structural explanations provided in a critical realist epistemology. This approach ensures that my research remains empirically grounded and practically relevant.

In a similar vein, I regard sociotechnical theory as directly compatible with this epistemological position, as both share the concern with connecting everyday practice to broader organisational and structural conditions. More fundamentally, sociotechnical theory also carries ontological implications: it assumes that the social and the technical cannot be meaningfully separated, but are co-constitutive elements of the same system. This view aligns with a critical realist understanding of reality as stratified and relational – where mechanisms, structures, and practices interact across levels producing observable phenomena. From this perspective, technology is not treated as an external or deterministic force, but as something that both shapes and is shaped by social action in social contexts, and vice versa. This makes sociotechnical theory not only methodologically useful, but also epistemologically coherent with a view of knowledge as historically, contextually, and culturally situated, and oriented towards understanding how different elements of sociotechnical systems co-produce outcomes in practice.

In summary, I tentatively and cautiously accept critical realism's ontological commitment within the frameworks of this thesis, I strongly endorse its epistemic relativism and judgement rationality in a pragmatic critical realist framework, which enables a coherent epistemological stance that bridges effectively with social constructivist-inspired approaches, thus supporting the aims and methods of my research.

4.4.5 A note on Subjectivity and Inquiry

In research based on qualitative data, subjectivity is not merely unavoidable – it is integral to the knowledge production process. Understanding and accounting for the researcher's role in shaping interpretations is essential for transparency and analytical depth.

Within a critical realist perspective, the researcher cannot be seen as a neutral observer but an active participant in the production of knowledge. The role of the researcher cannot be reduced to that of a neutral observer, but is instead understood as that of a theorising agent – constructing explanations, interpreting meaning, and making inferences about underlying mechanisms based on observed patterns. This view acknowledges that knowledge is not passively received but actively generated through engagement with the empirical world.

My background, experiences, and theoretical commitments have inevitably shaped the way I interpret the empirical material, the explanations I offer, and the mechanisms I propose. In many ways, these influences are difficult to fully identify or analyse, as doing so would require me to step outside of them – a position that is, by definition, inaccessible. I do not claim objectivity, nor do I strive for it. Instead, in alignment with Peshkin's view that subjectivity is not a problem to eliminate but a resource to acknowledge and reflect upon Peshkin (1988), I recognise that the insights presented here are theory-laden and shaped by the position from which I have conducted the research.

Here, the abductive character of the research process is also worth emphasising. Abduction has been described as a dynamic, iterative logic of inquiry in which observations are engaged through a back-and-forth movement between empirical material and theoretical concepts, allowing new insights to emerge that are both practically and theoretically meaningful (Hofmann, Paavola, & Raino, 2024; Van Hulst & Visser, 2025). In this sense, abductive reasoning resonates with the view of the researcher as an active theorising agent: insights emerge through an iterative interplay between empirical material and theoretical perspectives, where concepts are used both to interpret the data and to develop the most plausible understanding of it.

Although the findings are partial and situated, they nonetheless aim to offer valuable insights into the underlying structures and mechanisms that shape the development and implementation of autonomous systems, aligning with the purpose of this research.

4.4.6 Limitations

Like all research, this thesis has limitations that should be acknowledged. As discussed previously, the studies presented here should be understood as strategic empirical entry points into the broader process of designing, developing, and implementing autonomous mining systems. This approach has enabled depth at the expense of breadth and implies that the findings should be seen as partial and contextual, offering conceptual insights into parts of how such systems are shaped through organisational processes and how their implementation influences work and operator roles.

At the same time, the empirical material is drawn exclusively from the mining industry, which means that the findings cannot be generalised in a statistical sense. Instead, their value lies in developing theoretical and methodological perspectives that may be transferable to other settings where autonomous systems are introduced, provided that those contexts share relevant characteristics with mining.

A further set of limitations relates to the modes of data collection. Some of the workshops and interviews were conducted digitally, through platforms such as Microsoft Teams. While this enabled participation from a wider range of stakeholders and ensured continuity during the research process, it also constrained the possibilities to observe non-verbal cues, embodied interactions, and informal dynamics that might have been more accessible in face-to-face settings. In addition, much of the empirical material was originally collected in Swedish and later translated into English for the purposes of writing and dissemination. Despite careful attention to accuracy, it is possible that certain nuances or culturally embedded expressions have been lost or altered in translation.

Finally, there are limitations related to the researcher's role and methodological choices. My position, background, and theoretical orientation have inevitably shaped both the design of the research and the interpretations offered. While reflexive practices have been employed to make these influences visible, the findings remain situated and theory-laden. These limitations should not necessarily be understood as flaws but as conditions of qualitative inquiry: by concentrating on a limited number of sites and practices, the thesis has been able to provide empirically grounded insights into how autonomous systems are introduced in mining, while necessarily leaving the broader picture beyond its empirical scope.

5 Summary of Appended Papers

5.1 Paper I – Literature Review on Technology Development in Mining and Work

Lund, E., Pekkari, A., Johansson, J., & Lööw, J. (2024). Mining 4.0 and its effects on work environment, competence, organisation and society – a scoping review. *Mineral Economics, 37,* 827–840. https://doi.org/10.1007/s13563-024-00427-0

This paper presents a scoping literature review that explores how digitalisation and automation, conceptualised under the umbrella term Mining 4.0, are expected to reshape key areas of the mining industry. The review focuses on four interconnected domains: work environment, competences, organisation, and society. Work environment is based on an understanding that includes not only physical health and safety but also psychosocial conditions, task content, and opportunities for learning and development. In relation to the thesis, this paper also engages with the notion of sustainable technological change, understood here as technological development that explicitly considers its consequences for work and organisational practices. In this context, sustainable technological change is not limited to productivity or safety gains but also requires long-term investment in workforce development, local employment opportunities, and transparent communication with affected communities. Such measures are critical if new technologies are to contribute to socially sustainable transitions in mining.

The review shows that while questions of safety and efficiency dominate the literature, the effects of Mining 4.0 on broader dimensions of work environment are far less examined. This limited attention to work environment issues represents a central gap in current research – a gap that frames the empirical focus of the subsequent papers in this thesis and links directly to the overarching research questions, particularly research question (ii). The study applied a structured search strategy based on the PEO framework, resulting in the inclusion of 24 peer-reviewed articles, which were thematically analysed and categorised according to the four domains.

Human Factors in Technology Development for Improved Work Environments

The reviewed literature suggests that technologies such as automation and digitalisation can improve physical safety by relocating workers from hazardous areas to remote control environments. However, such improvements may come with unintended consequences – such as reduced cognitive and physical engagement, monotony, and social isolation. These findings suggest that while automation can reduce physical risk, it may also create new psychosocial challenges, particularly for operators whose work becomes more passive or surveillance-based. The literature underscores the importance of integrating human factors early in technology implementation to ensure that new systems support engaging, stimulating, and healthy forms of work.

Competence Based on Lifelong Learning and Multidisciplinary Teams

As highlighted in the literature review, technological development in mining is accompanied by a shift in competence demands – from site-specific manual skills to broader digital, analytical, and collaborative capabilities. Operators are increasingly expected to work in multidisciplinary teams, interpret system data, and troubleshoot problems in real time. These developments challenge traditional role boundaries and highlight the need for continuous competence development. The review notes a risk of polarisation, whereby some workers gain access to enriched roles while others may be marginalised. Ensuring inclusive and adaptive training structures is therefore essential if automation is to support sustainable and equitable transitions in operator work.

Learning Organisations Based on Sociotechnical Principles

The literature review also highlights the organisational dimensions of technological change. Digital systems can either centralise control or enable more decentralised and adaptive forms of organisation, depending on how they are implemented. Several authors advocate for sociotechnical design principles – such as operator autonomy, teamwork, and participatory learning cultures – to ensure that new technologies are integrated in ways that enhance rather than constrain human capabilities. These perspectives are particularly relevant for understanding how implementation strategies shape the roles and responsibilities of operators within evolving work systems.

Reinvesting in Mining Societies for Long-Term Sustainability

Although less developed in the publications found in this literature review, the societal implications of automation are significant. Reduced demand for low-skilled labour and a shift towards remote operations may weaken the economic and social fabric of mining communities. While not a central theme in the reviewed literature, fears of job loss frequently surface in public debate and resonate with these concerns, highlighting risks of polarisation and social fragmentation. The review suggests that sustainable technological change will require mining companies to invest not only in new systems but also in workforce development, local employment, and transparent communication with affected communities.

Concluding Reflections

This paper provides a broad overview of how digitalisation and automation are conceptualised in academic discourse and identifies critical knowledge gaps. While many publications anticipate improvements in safety and efficiency, there was strikingly limited attention to how Mining 4.0 affects the quality, meaning, and attractiveness of operator work. Empirical research on job content, task distribution, and social dynamics remains scarce, particularly concerning how new technologies reshape the everyday realities of operators in mining.

By highlighting this imbalance, the review motivates the empirical focus of the subsequent papers, which examine in greater detail how autonomous systems are designed, developed, and implemented, and what these processes mean for operator roles and organisational structures. In this way, the review supports the overall thesis aim of understanding how autonomous systems reshape operator work, by showing that existing research rarely considers these implications in depth. It also establishes a baseline for the progression of the thesis: Paper II turns to the perspectives of designers, Paper III to the implementation of autonomous systems, and Paper IV to the changing conditions of operator work. At the same time, the review makes visible the insufficient consideration given to work environment issues in existing literature. This recognition is central, as it underlines why studying the implications of autonomous systems for work is necessary if technological change in mining is to be socially sustainable.

5.2 Paper II – The Design of Autonomous Mining Technology

Lund, E., Johansson, J., & Lööw, J. (2024). The Designers' Perspective on Autonomous Mining Systems and Sociotechnology. *Mining, Metallurgy & Exploration, 41,* 647–657. https://doi.org/10.1007/s42461-024-00952-0

The second paper examines how designers and developers conceptualise the human–technology relationship in the development of autonomous mining systems. Unlike the subsequent papers, which analyse the implementation of autonomous systems, this study takes an upstream perspective by examining how designers and developers conceptualise the human–technology relationship during early phases of system development. Drawing on sociotechnical systems theory, the study investigates the assumptions that guide design choices and explores how these may influence future work environments. The paper addresses a critical but under-explored aspect of technology development in mining – namely, how human roles and responsibilities are envisioned during the early phases of system development, rather than only during implementation or use.

The study was conducted within the context of the EU project on autonomous mining systems (see Chapter 4 and Section 4.1.2 for details), and the findings should be understood within this European–Swedish mining context.

The aim of the study was to explore how technology developers understand the role of humans in relation to autonomous mining systems, and how their perspectives inform the design of future mining work systems. This aligns with the broader purpose of the thesis by offering insight into research question (i). The study also provides a conceptual entry point to understanding how these upstream decisions may shape downstream experiences of operator work – thereby also contributing to research question (ii).

Empirically, the paper is based on five semi-structured workshops with designers and developers involved in the EU project focused on autonomous mining solutions (see Section 4.1.2 in Chapter 4). All participants were based in a European mining context, and the workshops were organised according to different technological focus areas, including fleet management, robotised inspection, and autonomous material handling. The analysis followed an inductive thematic approach and resulted in three main themes: the technological system, mediating processes, and the social system. These themes reflect how the participants envision the interaction between humans and technology in future autonomous mining operations.

The analysis focuses specifically on the perspectives of designers and developers, rather than on how autonomous systems currently function in operational settings. The technological solutions under discussion were at an early, conceptual stage of development, with many elements remaining speculative. Although the EU project concluded with a demonstration of an autonomous loading and dumping sequence using actual mining machines in a test mine, this served primarily as a proof of concept rather than a system ready for implementation. Accordingly, the envisioned human–technology interactions should be understood as prospective and exploratory – reflecting design assumptions and intentions that may or may not be realised in future mining operations.

The Technological System

According to the designers and developers participating in the study, the primary goal of automation is to increase efficiency – for example, by enabling continuous operation during blasting and shift changes. The envisioned technological system is also expected to provide operators with real-time data, instructions, and recommendations. In some areas, participants described decision-making as already being delegated to the system itself – such as in draw point selection – while in others, they anticipated that humans would be expected to support the autonomous system, rather than the reverse. These accounts reflect a perceived shift in the division of labour, with potentially significant implications for how operator roles are configured in future mining environments.

Mediating Processes

Based on the participants' accounts, the analysis suggested four mediating processes that help make sense of the interaction between operators and autonomous systems: competence, trust, safety, and usability. These should not be read as a definitive framework, but rather as an analytical way of articulating how designers and developers describe the interplay between technical and social elements in autonomous mining systems. While the processes provide a useful lens on how developers envision future operator roles, further empirical and theoretical work is needed to assess their broader applicability and significance.

The Social System

While the technological system was often described in terms of increasing autonomous system functioning, participants consistently emphasised the continued importance of the social system – in particular, the role of operators. According to the designers and developers, operators are expected to perform maintenance, initiate tasks, monitor operations, intervene when necessary, and make strategic decisions. Their accounts suggest that even in highly autonomous systems, human input will remain essential, especially in areas such as situational judgement, problem-solving, and coordination across functions.

Concluding Reflections

This paper offers both empirical and theoretical contributions to the thesis. Empirically, it provides insight into how designers and developers conceptualise the human element in system design – a perspective often overlooked in research about autonomous mining systems. The analysis can be understood as a model of how technology developers envision the interaction between humans and autonomous systems, rather than an account of how these systems function in operational practice. This model sheds light on the assumptions that underpin design choices and how they may shape future operator roles.

Theoretically, the paper proposes mediating processes – including trust, competence, safety, and usability – as an analytical way of understanding how designers describe the relationship between technical systems and social systems. These processes should be seen less as a definitive framework and more as an interpretive tool for making sense of how designers articulate the relationship between technical and social elements. While they point to the relational fabric through which autonomous systems may be made workable in practice, further empirical and theoretical work is required to determine their scope and significance. In this sense, the analysis offers a tentative extension of sociotechnical perspectives, while also highlighting that existing frameworks may need refinement to capture the complexity of contemporary production systems shaped by autonomous mining systems.

Taken together, the findings highlight how early design decisions – including assumptions about operator roles and human–technology interaction – shape the conditions under which autonomous technology is later implemented, experienced, and made workable in practice. They also underscore the importance of engaging end-users, particularly operators, already in the early design phases, since it is their knowledge and work practices that ultimately shape whether autonomous systems become workable in practice. The paper supports a more human-centred approach to autonomous mining systems – one that recognises both the enduring and evolving role of the operator for work systems that are not only technically robust but also ethically and socially viable.

In the context of the thesis, this paper demonstrates that the reshaping of operator work begins already in the design phase, where developers' expectations of human–technology interaction prefigure the conditions under which autonomous systems are later implemented and experienced.

5.3 Paper III – The Implementation of Autonomous Mining Systems

Lund, E., & Nygren, M. With one foot in the future – Situating Autonomous Systems in Mining through Communities of Practice. SUBMITTED TO: *Journal of Organizational Change Management,* September 2025.

This third paper contributes to the thesis by exploring the implementation of autonomous systems in mining, with a focus on how meaning, engagement, and learning emerge through practice. Rather than viewing implementation as a top-down, technical rollout, the paper conceptualises it as a socially embedded process shaped by the everyday actions and interactions of those involved. Drawing on the theory of Communities of Practice developed by É. Wenger (2008), the paper investigates how mutual engagement, joint enterprise, and shared repertoire developed around the implementation of an autonomous haulage system in an open-pit mine in northern Sweden. As elaborated in Chapter 4, this case provides a specific national and organisational context, and the findings should be understood as situated within that setting rather than as universally representative.

Mutual engagement refers to the ongoing interactions and relationships through which participants coordinate activities, negotiate meaning, and build trust – it is through this engagement that a community becomes socially cohesive (É. Wenger, 2008). Joint enterprise captures the collective purpose that members pursue and continually renegotiate, shaped not only by formal goals but by their own interpretations of what matters. Shared repertoire includes the routines, tools, language, and stories that the community develops over time and draws on to make sense of their practice and communicate effectively.

Implementation Through Community Practice

The empirical basis for the paper is a qualitative case study combining 24 semi-structured interviews, field observations, and field notes collected over multiple visits to the mine site. The study focuses on a project implementing large, driverless haulage trucks managed by a centralised fleet system. The analysis highlights how the introduction of this system gave rise to a community of practice, within which participants developed a shared understanding of their work, the system, and its broader significance. These understandings were not fixed in advance, but negotiated through experience, problem-solving, and interaction with both colleagues and technology.

The analysis shows that the implementation project was fuelled by a shared sense of enthusiasm and a commitment to solving new challenges together, i.e., mutual engagement. Participants described a collective process of learning, improvisation, and relational coordination. The joint enterprise that emerged was not a reproduction of top-down objectives, but a negotiated sense of purpose centred on safety, efficiency, and being part of something new. Participants viewed the project as a meaningful investment in the future of mining, positioning themselves as contributors to organisational progress. The shared repertoire included both formal routines and informal insights into how the system worked in practice, as well as strategies for promoting legitimacy and acceptance across the organisation.

Concluding Reflections

This paper shows that the implementation of AHS is not merely a matter of technical integration, but a social process shaped by meaning-making and learning in practice. In this case, the technology became workable through the formation of a community of practice, where shared engagement, negotiation, and adaptation anchored the system in everyday work. The system's success depended not only on its functionality but on the development of relational and interpretative practices. Through mutual engagement, participants built shared understandings and a sense of ownership that made the technology meaningful in context. In relation to the thesis, this paper addresses research question (ii) by showing how implementation reshapes operator practices through processes of meaning-making and engagement.

Importantly, this community-based engagement also helped legitimise the system within a sceptical organisation. Early resistance gradually gave way to broader acceptance, not through top-down persuasion, but through the community's active efforts to demonstrate value and build trust across organisational boundaries. In offering this account of implementation, the paper contributes a perspective still uncommon in mining research: one that highlights how autonomous systems gain traction not through deployment alone, but through the social and practical labour that renders them usable and real.

While grounded in extensive empirical material, the analysis reflects an interpretative approach informed by a constructivist perspective. Rather than presenting a definitive account of the implementation process, the paper offers a narrative that foregrounds meaning-making and social learning.

This represents our reading of the case, informed by the Community of Practice theory developed by É. Wenger (2008), aimed at making visible the relational and practical dynamics through which autonomous systems become embedded in organisational life.

5.4 Paper IV – Implications of Cyber-Physical Mining Systems for Operator Work and Organisation

Lund, E. Autonomy for whom? Implications of Cyber-Physical Mining Systems for Operator Work and Organisation. SUBMITTED TO: *Applied Ergonomics,* November 2024.

This fourth and final paper builds on the same empirical case as PAPER III, examining the implementation of a cyber-physical mining system – the Autonomous Haulage System – from a work-system perspective. It explores how digital integration and advanced control technologies reshape the relations between human, technological, and organisational elements, with particular attention to operator roles and coordination practices. Drawing on an explorative case study in a Swedish open-pit mine, the analysis applies Balance Theory (Smith & Sainfort, 1989; Carayon & Smith, 2000) to interpret how work and organisational conditions are reshaped as control and responsibility are redistributed between humans and technology.

While PAPER III examined the social learning processes during implementation, this paper focuses on how the ongoing integration of autonomous systems changes the nature of operator work, organisational structures, and everyday practices. The analysis takes a systems-oriented perspective, showing that technological developments not only transform specific tasks but also alter how work is coordinated and experienced.

The study is based on interviews, observations, and document analysis conducted during the implementation of the AHS in an open-pit copper mine in northern Sweden. Although the trucks operate autonomously, human operators remain essential to supervision, coordination, and adaptation. The paper contributes to the thesis by showing how mining work is reorganised through new constellations of control, structure, and responsibility, and how these shifts influence both the experience and organisation of work.

The Findings

The findings are presented according to the five elements of Balance Theory: *physical environment*, *work tasks*, *technology*, *organisation*, and *experience* *of work*. Together, these elements illustrate how the implementation of an autonomous haulage system transforms the work system as a whole.

The *physical environment* of operator work was generally described by participants as improved. Operators involved in this work system reported that they were no longer exposed to noise, vibration, and collision risks associated with driving heavy trucks on rough roads for long hours. However, they also noted that the risk was not removed but redistributed: on-site operators still spent long hours in mine vehicles, and physical strain persisted, though for a smaller group of workers.

Regarding *work tasks*, participants described the transition to the autonomous system as involving more varied and responsibility-laden roles. On-site operators were portrayed as problem solvers who handled disturbances, performed troubleshooting, and ensured the continuity of operations. Control-room operators were described as managing and coordinating fleets of autonomous trucks, maintaining production flow, and overseeing system safety. These accounts indicate a shift from repetitive manual driving to roles that require analytical thinking, situational awareness, and cross-functional communication.

The *technological* dimension was portrayed as characterised by both precision and constraint. Participants noted that the AHS brought greater predictability and coordination, though often at the cost of flexibility. Operators explained that all actions had to follow predefined routines, leaving little room for improvisation. While the technology was viewed as enabling safer and more stable operations, it was also seen as demanding close collaboration between on-site and control-room personnel, since many situations still required human interpretation and intervention.

At the *organisational* level, the implementation was described as being accompanied by increased standardisation and bureaucratisation. Roles and procedures became more formalised, and training requirements expanded as new competences were needed to operate and maintain the AHS. Participants also reported a marked reduction in informal contact among colleagues and supervisors, creating risks of social isolation and weakening everyday communication. Maintaining organisational balance therefore depended on fostering collaboration, communication, and mutual understanding across different work roles.

The analysis of the *experience of work* presents a mixed picture. Former truck drivers described their new roles as more stimulating and meaningful, offering greater responsibility and engagement. At the same time, they reported increased stress, less flexibility, and reduced social interaction. Everyday activities such as taking breaks had to be coordinated with production procedures, reflecting a growing proceduralisation of work. The new system was thus experienced as bringing both enrichment and constraint:

it created more qualified and significant work but also tighter coupling to organisational rules and technical routines.

Concluding Reflections

The paper concludes that the implementation of the AHS does not diminish the importance of human work but redefines it. Operators remain essential for supervision, coordination, and the overall stability of the work system. From a Balance Theory perspective, technological precision and safety improvements must be balanced with organisational support and social cohesion to sustain a well-functioning system.

The study shows that achieving and maintaining balance in autonomous, cyber-physical mining systems is not a one-time accomplishment but an ongoing organisational responsibility. The results emphasise that technological performance depends equally on collective engagement, communication, and continuous learning. In this way, the paper reinforces the broader argument of the thesis: that the transformation towards more autonomous technology in mining should be understood not as the removal of human involvement, but as its reconfiguration within new, interdependent relations between humans, technology, and organisation.

6 Discussion

The design and development of autonomous mining systems unfold as a complex and fragmented process, involving multiple actors and guided by technically-oriented logics that unintentionally marginalise operators and social and human perspectives.

This chapter discusses the findings of the thesis in relation to its overarching purpose. The next section focuses on the research questions, followed by a discussion that places the findings within broader theoretical debates and explores their practical and societal implications. Together, these sections provide the foundation for the overall conclusions of the thesis.

6.1 From Design Logics to Rebalancing: Autonomous Mining Systems and Operator Work

In addressing the research questions, four interrelated findings are presented below. Together, they show how underlying design logics shaped the positioning of operators in the development and use of autonomous mining systems, from the dominance of technically-oriented design priorities and the resulting marginalisation of operators, to the reshaping of their work through adaptation and reconfiguration, and finally to the rebalancing of social and technical elements during implementation.

6.1.1 Design logics and operator marginalisation

This subsection examines how underlying design logics, together with the assumptions and priorities embedded in them, shaped the positioning of operators in the development of autonomous mining systems. Across the empirical material, four interrelated themes can be identified.

First, the findings show that the design and development of autonomous systems in mining are shaped by a dominant technically-oriented logic. System performance, optimisation, and efficiency are prioritised, while social and organisational concerns tend to appear later in the process. This pattern emerges across a broad landscape of actors – OEMs, mining companies, software developers, and universities – and varies somewhat in its expression and emphasis, yet remains consistently shaped by a technically-oriented design logic.

This pattern is evident in Paper I, which highlighted that research on Industry 4.0 and digitalisation in the mining sector pays relatively little attention to operators and work environment issues. Although a few exceptions exist, the review revealed an overall lack of attention to this perspective. A similar tendency was observed in Paper II, which examined how designers and developers of autonomous mining systems view the role of operators in relation to the technologies they create. The operator perspective was not a natural or explicit part of their design process. Yet, when asked directly, participants engaged readily and with considerable interest in such questions, including issues of trust in technology and the interaction between operators and the systems being developed. These findings suggest that the relative absence of operator perspectives and broader social concerns such as work environment, both in the literature and in design and development practice, cannot be reduced to a simple lack of interest. Rather, it appears to be linked to more complex constellations that shape what counts as relevant or legitimate in these arenas – a complexity that is important to acknowledge without reducing it to a single cause.

Additional observations from my field notes (see Section 4.2.4 for a description) support this picture. Design and development unfolded in complex constellations across parallel arenas, including in-house R&D departments at mining companies, OEM demonstration facilities, and collaborative projects with universities. In these settings, a technically-oriented logic was consistently foregrounded: efficiency and optimisation were emphasised, while operator perspectives and work environment concerns tended to remain secondary. What emerged was not so much a deliberate exclusion of these perspectives, but a marginalisation as a by-product of prevailing priorities and assumptions. Even when acknowledged in principle, operators were typically positioned as end-users who must adapt to predefined systems, rather than as active contributors in shaping technology for work. Taken together, these observations reveal a recurring pattern in which technically driven design priorities tend to sideline social and organisational concerns.

Second, the technically-oriented design logic described above produced a pattern of *marginalisation by default*, whereby operator roles and work environment issues were sidelined unintentionally as a result of prevailing design priorities.

This dynamic is visible throughout the empirical material. It risks producing systems that are technically robust but socially fragile, a condition that reflects an underlying vulnerability tied to questions of work environment and the social embedding of technology, since integration with organisational practices and operator competencies is left to later stages, such as moments of practice and implementation. Such patterns were already visible in PAPER I, which showed that research on Industry 4.0 in mining paid little attention to operators and work environment issues, and in PAPER II, where designers and developers only reflected on operator roles when explicitly prompted to do so. The case study of the autonomous haulage system (PAPERS III–IV) further demonstrated how this marginalisation created vulnerabilities, as the transition involved a fundamental reshaping of operator work. While the system was technically functional, the reconfiguration of tasks and responsibilities introduced risks of social fragility, including workload unpredictability, reduced opportunities for interaction, and a heightened sense of uncertainty about how work should be carried out and supported. Taken together, these dynamics provide the point of departure for the third finding:

Third, the marginalisation by default also means that operators are required to adapt to systems that have largely been defined without their input.

The case study of the autonomous haulage system (PAPERS III–IV) showed that this adaptation involved a substantial reshaping of operator work. Work became more technically demanding, requiring advanced system knowledge and the ability to manage complex interactions between machines and personnel. At the same time, the conditions of work continued to hinge on social and collaborative dimensions, as operators needed to coordinate with colleagues, engineers, and control room staff to keep the system running. In this sense, the marginalisation inherent in a technically-oriented design logic does not eliminate the role of the operator, but reconfigures it in ways that establish new and often more demanding conditions for their work.

These shifting demands carry important implications. They suggest that much of the viability of autonomous systems in mining depends on operators demonstrating the flexibility and adaptability required to make them work in practice. In this way, the absence of operator perspectives in design and development stages is not without consequence, but creates a dynamic in which operators are often left to compensate for decisions, gaps, and assumptions embedded in earlier stages of system design.

The findings highlight a central tension in the design and development of autonomous mining systems: while the stated goals often include improving safety and working conditions, the prevailing design logic continues to treat social and organisational integration as secondary. This tension echoes the paradox introduced earlier – operators remain present in principle but peripheral in practice, positioned as necessary backstops to technology rather than as central actors in its design. Understanding this mechanism helps explain why implementation later requires renegotiation and rebalancing.

6.1.2 Implementation as rebalancing

This subsection analyses implementation as a process of rebalancing, where the dynamics of marginalisation identified in the design stage are confronted and adjusted in practice. The focus is on how operator roles, practices, and organisational arrangements are reshaped as autonomous systems come into use, while also showing how earlier design logics are challenged in this process. As the systems moved from development into daily use, the dynamics identified in the previous section did not disappear but were transformed. They re-emerged in new ways as questions of coordination, responsibility, and meaning became central to everyday operation.

Finally, the analysis shows that the fourth and final finding concerns implementation and involves a dual process of rebalancing: on the one hand, a social rebalancing of roles, relationships, and meanings within everyday work; and on the other, an organisational rebalancing of responsibilities, procedures, and coordination structures. Both dimensions required ongoing negotiation, interpretation, and collaboration beyond formal groupings.

Taken together, the dynamics discussed in Papers III–IV point to implementation as a sociotechnical process of alignment, where the characteristics of technology and work practices are mutually adjusted. Implementation depended on operators, supervisors, and engineers engaging in collective sense-making and developing new work practices to render the system functional and meaningful in everyday operations. Within the interdependent and high-risk setting of mining, this alignment work was both necessary and fragile, revealing the contingent character of autonomous system integration.

What this reveals is that implementation was not simply about fitting a technical system into place, but about negotiating a workable balance between technical demands and social realities – a balance that entailed shifts of responsibility and learning, as well as both opportunities and risks for operator work. These risks included workload unpredictability and increased social and functional isolation (fewer spontaneous contacts and collaboration increasingly confined to digital interfaces). In this sense, the social and organisational processes that underpinned implementation were not secondary but central to sustaining technology in daily operations.

The case study of the autonomous haulage system illustrates how these dynamics unfolded in practice. Paper III showed that integration was sustained through the emergence of a community of practice, in which participants engaged in joint problem-solving and shared routines that anchored the system in everyday work. Beyond enabling learning through collective efforts, this process was also tied to identity: many operators expressed pride in contributing to what they perceived as the future of mining. However, this sense of engagement coexisted with organisational ambivalence. Pride and legitimacy reinforced commitment within the group, yet scepticism towards both the technology and the project persisted elsewhere in the organisation, meaning that the group's value had to be continually demonstrated before it was fully recognised. Although identity and pride strengthened motivation, they did not offset reduced informal contact or the perceived workload during disturbances, suggesting distinct mechanisms at play.

Beyond the immediate workgroup of operators, implementation also affected the organisation more broadly. As discussed in Paper III, this was not only a matter of adjustments in local work routines but of the company as a whole learning to accommodate and integrate the new system. Over time, new practices emerged informally to compensate for limitations in formal procedures, illustrating how collective, social processes became essential for embedding the system. These dynamics also pointed to a fundamental tension: they enabled the system to function in daily operations, yet at the same time revealed how dependent implementation was on fragile forms of social integration. In this sense, increased formalisation did not only stabilise production but also highlighted the system's sensitivity to disruptions by extending social dependencies.

On a broader level, the introduction of autonomous mining systems such as the AHS reshaped organisational dynamics in ways that both enabled and constrained work. Paper IV showed that the creation of new roles and responsibilities was accompanied by a growing reliance on formalised procedures and training, reinforcing a more bureaucratic and standardised approach to work. At the same time, the system generated new interdependencies that required closer coordination across roles and organisational boundaries. These shifts also carried risks: as fewer personnel were directly involved in daily operations, opportunities for informal interaction diminished, raising concerns about isolation and the weakening of social ties. Rather than a smooth organisational adjustment, the process was characterised by competing pressures – on the one hand, enhanced safety, clarity, and standardisation; on the other, increased rigidity, heavier demands on learning, and greater vulnerability in social integration. Taken together, these dynamics show that the implementation of autonomous mining systems transforms not only operator roles but also the organisational fabric and everyday practices through which work is accomplished.

In short, and consistent with the principles of Sociotechnical Systems

Theory, this section demonstrates that implementation is best understood as a process of social rebalancing, through which social concerns and operator perspectives – previously sidelined by technically driven design priorities – are brought onto the agenda through learning, negotiation, and collective adaptation.

6.2 Towards a Social Understanding of Autonomous Mining Systems

This section highlights how the design and implementation of autonomous systems are shaped by broader design logics, organisational dynamics, and operator practices. By describing patterns of *marginalisation by default* and introducing the notion of *implementation as rebalancing*, the thesis provides a vocabulary for understanding how autonomous mining systems transform operator and organisational dynamics in mining. The analysis also shows how sociotechnical theories can be deepened by attending to design practices, shifting logics, and the collective processes through which technology becomes embedded in organisations. Finally, the discussion highlights emerging implications for social and organisational challenges and implications for work and society.

6.2.1 The Ironies and the Question of Rebalance

This thesis contributes to research on work in autonomous systems and sociotechnical systems in two main ways. The first contribution lies in developing a more nuanced understanding of the mechanisms through which operators become sidelined in the design and development of autonomous mining systems. Rather than resulting from deliberate intent, this marginalisation emerges as a by-product of structural conditions and technically-oriented logics that shape how technology is conceived and integrated into work. These structural conditions are often overlooked in existing accounts of automation, including the *Ironies of Automation* (Bainbridge, 1983; Endsley & Kaber, 1999).

What emerges from this can best be understood as a form of *reactive* design logic: rather than proactively considering questions of operator competence, learning, and work environment in the early stages of development, these issues are typically addressed retrospectively, once technical architectures have already been defined. In this sense, social dimensions of work are subordinated to technical optimisation, and only come onto the agenda after the system has taken shape. As Bainbridge (1983) observed, such strategies risk leaving operators "in the loop" only residually, with reduced agency and limited influence over system behaviour. These dynamics illustrate that the very tendencies leading to automation's ironies also create the need for social rebalancing once systems are put into practice.

While the analysis points to a dominance of technically-oriented priorities, it also suggests that such dominance is never absolute. Development processes are inherently dynamic and involve continuous adaptation among different forms of expertise, interests, and constraints. As Lööw (2021) argues, design can never be "right" from the start; rather, technologies and their surrounding systems must be configured and reconfigured through iterative feedback, adaptation, and negotiation. From this perspective, the challenge extends beyond the design and developmental phase itself: it concerns the creation of organisational and procedural conditions that allow this adaptation to continue downstream – as technologies are implemented, adjusted, and sustained in practice. In other words, technology development must be conceived not as the production of a finished artefact but as an ongoing process that integrates technical, organisational, and social systems.

This pattern echoes broader Nordic findings on digitalisation and work. Research by Rolandsson and Dølvik (2021) shows that technological change in manufacturing, services, and care has unfolded as a gradual reconfiguration of work rather than a disruptive transformation. Human participation and learning remained central even in highly automated contexts, pointing to the same need for continual rebalancing between technical and social logics that this thesis identifies in autonomous mining systems.

The second contribution is to understand implementation as a process of *rebalancing* between the technical and the social – where the logics that marginalised operators in design and development are confronted and renegotiated in practice, through the everyday efforts of operators, supervisors, and engineers involved with the system. Whereas the design stage often sidelines operators and social concerns, these questions re-emerge as significant considerations during implementation, when autonomous mining systems must be integrated into daily production. This confirms that implementation is best understood as an ongoing negotiation in which questions of operator competence, work environment, and collaboration regain salience. This analysis builds on sociotechnical theories emphasising mutual shaping (Mumford, 2006; Carayon & Smith, 2000), but extends them by showing how the social side of the system reasserts itself in practice through the negotiations and collaborative efforts that sustain the technology in use in line with É. Wenger (2008)'s theory of Communities of Practice.

The thesis shows that the marginalisation of operator perspectives described in the previous section can also be understood in terms of automation logics. The design and development of autonomous mining systems most closely resembled what Parasuraman (2000) describe as the Default Strategy to automation (see Def. 1): design guided by what can be automated, rather than what should be. This is noteworthy given the growing emphasis on human-centred and systems integration approaches in contemporary automation research and practice related to mining (Rogers et al., 2019; Burgess-Limerick, 2020, 2025) and also in the growing literature related to the concept of Industry 5.0 (European Commission, 2021). Despite these developments, the empirical material suggests that such perspectives have yet to become fully embedded in industrial practice, where design processes remain primarily driven by technical feasibility and performance goals.

However, once systems move into implementation, this logic is challenged and renegotiated in practice. As questions of operator competence, work organisation, and social integration come more clearly into view, the logics at play no longer align solely with that of the Default Strategy but also bear resemblance to other approaches to automation. In practice, task allocation sometimes reflects the classic principles of the Fitts' List (see Def. 2) (Fitts, 1951), where repetitive and physically demanding tasks are automated while more complex or variable activities remain human. One example of this is the AHS described in PAPERS III–IV, where repetitive haulage is handled by technology and strategic decisions are handled by operators. In other instances, arrangements echo elements of an Adaptive Approach to Automation (see Def. 3) (Parasuraman, 2000), with operators overseeing or assisting multiple machines. Such observations resonate with arguments made by Rogers et al. (2019), who suggest that an updated version of the Fitts' List could provide a viable basis for the mining industry – but only if task allocation is guided by a human-centred rather than a technology-centred approach.

While operators were positioned peripherally in the design and development phase, this thesis shows that, in implementation and use, their roles remained active and consequential, particularly in key tasks such as monitoring, coordination, and taking over control in disturbances. On a task level, this is on par with Bainbridge (1983)'s analysis of operator roles in automatic systems, where operators are left with residual functions – overseeing processes and intervening only when things go wrong. Yet, while the tasks identified here are indeed similar in form, this study reveals a rather different account of how such work unfolds in practice.

Rather than being marginalised, operators in autonomous mining systems remain deeply engaged in system operation. Their work involves continuous coordination, planning, and preventive efforts to sustain production across a dynamic and interdependent process. This difference likely reflects the inherent complexity of the mining process – a tightly coupled and variable system that requires operators to remain actively within the control loop, rather than being displaced by autonomous mining systems, or residually with limited control and influence over the technological system (cf. Bainbridge, 1983). Under such conditions, human involvement cannot be eliminated; it remains essential to ensure safety, manage contingencies, and maintain production flow.

However, this does not mean that all aspects of work necessarily improve with autonomous mining systems. As the thesis also demonstrates, the reconfiguration of work brings its own tensions and trade-offs. While some aspects, such as safety may be strengthened, others – including social cohesion and the experience of connectedness – may be weakened or challenged. The increased spatial and temporal dispersion of autonomous mining systems contributes to new forms of isolation and dependence on system performance. The result is a complex picture in which autonomous mining systems both sustain and transform human involvement, challenging simple dichotomies between exclusion and empowerment.

6.2.2 Practice and the Social Embedding of Technology

Building on the previous discussion of automation logics and rebalancing, this section turns to the social and practical dimensions of how such rebalancing takes place in daily work. Here, insights from Communities of Practice theory developed by É. Wenger (2008) provide a lens for understanding how this rebalancing unfolds, according to which autonomous mining systems are not simply introduced but become established through processes of learning, meaning-making, adaptation, and coordination. Operators, engineers, and managers engage in joint problem-solving, develop shared repertoires for handling new situations, and negotiate the meaning of the technology for their work. In doing so, they also renegotiate aspects of their occupational identities and roles, positioning themselves in relation to the technology and to one another. In this sense, implementation is not only about technical integration, but about the collective practices of meaning-making and identity formation that allow the technology to take root in the organisation. Similar conclusions have been drawn in Nordic research on digital transformation of traditional work (Rolandsson & Dølvik, 2021), which found that successful implementation depends on broad worker participation and continuous joint problem-solving rather than technical optimisation alone. While the perspective of Communities of Practice highlights how implementation unfolds through local processes of learning and negotiation, sociotechnical approaches such as Balance Theory provide a complementary view of how stability and change are managed at the system level.

From the broader theory of Sociotechnical Systems Theory, and more specifically through the lens of Balance Theory, the findings presented in this thesis resonate with Balance Theory (Carayon & Smith, 2000). In some respects, the autonomous mining systems examined in this thesis appeared to enhance balance – by improving safety, providing more stimulating work, and reducing repetitive strain. In other respects, they appeared to create new imbalances in the interplay between technology and work – by reducing discretion, increasing isolation, and embedding work in more rigid organisational structures. Balance Theory emphasises that balance must be understood in relational terms: strains or shortcomings in one dimension of work can sometimes be compensated for by improvements in another. This builds on the core idea of joint optimisation of technical and social dimensions in the sociotechnical system (Trist & Bamforth, 1951; Trist, 1981; Mumford, 2006).

In this thesis, however, balance is also shown to be a profoundly social process. The design and development of autonomous systems create both the conditions for, and the need to, continually rebalance relations between the technical and the social. This rebalancing is not a static adjustment between system components, but an ongoing activity that unfolds through social interaction, coordination, and learning. While Carayon and Smith (2000) and Carayon et al. (2015) describe rebalancing primarily in terms of relations among the elements of a sociotechnical system, the actors who enact these adjustments tend to remain implicit. By contrast, the present study makes these actors visible, showing how rebalancing occurs as a dynamic and organic social process, understood here through the lens of Communities of Practice (É. Wenger, 2008).

The study therefore underscores and echoes a central lesson for contemporary debates on autonomous technology in mining: technological performance is deeply intertwined with, and contingent upon, social factors. Designing for efficiency without simultaneously designing for human engagement risks producing systems that are technically robust but socially fragile.

These dynamics are also evident at the organisational level, where autonomous mining systems reshape competence demands and working conditions in ways that combine opportunities with new challenges. On the one hand, new operator roles evolved, along with system-level thinking and greater responsibility for safety and coordination. On the other hand, these changes bring psychosocial risks: greater unpredictability of workload, increased isolation, and the experience of heightened responsibility. Such dynamics underline the importance of organisational strategies that integrate competence development with active measures to safeguard psychosocial health and well-being.

The analysis also points to the temporal dimension of implementation. Insights from Communities of Practice theory suggest that the forms of engagement and learning that sustained the new system are dynamic. They evolve, stabilise, and sometimes dissolve as work practice matures (É. Wenger, 2008). Understanding how these trajectories unfold over time will be central for future research on the long-term embedding of autonomous systems in mining.

At the societal level, the findings suggest that automation should not be understood in binary terms of either substitution or augmentation. The thesis nuances this understanding, showing that autonomous systems reshape rather than replace human labour, with consequences for roles, responsibilities, and organisational dynamics. This perspective complicates dominant narratives of job loss and points to broader questions about the distribution of responsibility and control in technology-intensive industries. It also draws attention to a potential paradox: while automation promises efficiency, it may in practice reinforce pressures to accelerate production and intensify work.

As noted in the introduction, debates about automation and AI unfold against a wider backdrop of deindustrialisation, labour shortages, and political concerns about industrial competitiveness. In this context, autonomous mining systems are frequently presented as part of the solution: a means of sustaining productivity and making the industry more attractive to new generations of workers. The findings of this thesis suggest a more nuanced picture. The findings of this thesis reaffirm and nuance a well-established insight: autonomous systems do not simply replace human labour, but reshape roles, responsibilities, and organisational dynamics in ways that carry both opportunities and risks.

Looking ahead, ongoing developments in AI and digitalisation suggest that the questions raised in this thesis will remain highly relevant. As algorithmic forms of decision-making become more common in industrial contexts, issues of discretion, trust, and professional identity, already evident in other sectors (Ranerup & Svensson, 2023, 2024; Germundsson, 2025), are likely to gain importance also in mining. In this sense, long-standing concerns about participation, influence, and the psychosocial work environment (Thylefors, 2019; J. Johansson & Abrahamsson, 2019) intersect with emerging ethical questions about responsibility and human experience in relation to intelligent systems (Fischer & Frennert, 2025).

To summarise, the findings of this thesis point to a set of emerging psychosocial and organisational dynamics that accompany the integration of autonomous systems in mining. For instance, increased formalisation and tighter coupling between human work and system performance concentrate responsibility and temporal pressure on fewer individuals, and educed opportunities for spontaneous coordination and informal collegial exchange challenge social support. Together, these dynamics illustrate how the social rebalancing that sustains autonomous systems also generates new forms of pressure, highlighting the need for organisational arrangements that preserve discretion, facilitate peer interaction, and support ongoing competence development.

6.3 Concluding Reflections

The thesis has shown that the design and development of autonomous mining systems unfold as a complex and fragmented process, involving multiple actors and guided by technically-oriented logics that often marginalise operators and social perspectives in unintended ways.

The approach taken in this thesis, combining an operator-centred perspective with a sociotechnical framing, demonstrates the value of studying autonomous technology as a process that spans design, implementation, and everyday use. Focusing on work practices and organisational dynamics, and processes has made it possible to reveal how autonomous systems are enacted and sustained in practice, rather than treating them as fixed technical artefacts.

In doing so, the analysis shows that implementation emerges as a moment of rebalancing, where negotiation, meaning-making, and social dynamics continually reshape both technology and work.

Concerning the logics and priorities that guide design and development, the thesis shows that a technically-oriented logic tends to dominate. System performance, optimisation, and efficiency are foregrounded, while social and organisational considerations appear downstream. In this context, operators are not deliberately excluded but are often *marginalised by default*: their roles and work environment concerns are sidelined as an unintended by-product of prevailing design priorities and automation logics. This positioning reflects broader complex constellations in the innovation landscape (OEMs, mining firms, software vendors, and universities) rather than a single cause. It risks producing systems that are technically robust yet socially fragile.

The thesis also indicates that such imbalances are never fixed. Design and development unfold through ongoing negotiations and re-alignments, where actors continuously reinterpret priorities and constraints. From this perspective, the development process can be understood not as an attempt to design “the right system” from the outset, but as the creation of conditions that enable continuous rebalancing between technical and social considerations.

Concerning how implementation reshapes roles, practices, and organisational dynamics, the thesis conceptualises implementation as a process of *rebalancing*. Earlier design assumptions are confronted with the realities of work, and the system is sustained through learning, negotiation, and collective adaptation. Insights from the theory of Communities of Practice illuminate how shared repertoires, meaning-making, and identity work support integration, while also showing the fragility of such arrangements. From this perspective, the social and the technical are not separate or hierarchical domains, but continuously co-constituted through practice – a relation that requires ongoing attention and rebalancing over time.

Altogether, the thesis underscores the need to view sociotechnical change as an ongoing, negotiated process – one that requires sustained attention to how technical and social considerations are continuously rebalanced in practice. Without wise and reflective attention to human and organisational dimensions, such efforts risk reproducing new psychosocial and organisational tensions, underscoring that resilience depends as much on human relations and participation as on technical reliability.

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7 Appendix

7.1 Interview Guide for Focus Groups

Each focus group followed the same overarching question, which was adapted to the specific technology being designed and developed within the respective work package (WP). Below, an example of the interview guide is provided to illustrate how the questions were formulated and tailored to the focus group context.

- What is the human's role in working with the Connectivity and Positioning technology developed in WP3?
- In what way (how and where) does the technology interact with the workers?
- How does the technology and the human workers relate to each other?
- Is there a specific competence or skill that will be necessary or beneficial for future workers when working with the connectivity and positioning technology?
- What predicament does a deviation of the expected functioning of the connectivity and positioning technology place a human worker in?
  - if general functioning drops, fails or works poorly? How about communication?
  - in case of technical deviations, such as interruption in electric supply?
  - if the system is stressed by a fire or emergency?
  - if operation and maintenance tools are used incorrectly?
  - in case of competing operations? I.e., that the technology has a disruptive effect on other aspects of the workplace. Can the worker influence the system?

  - if positioning data is leaked, such that it can be misused?

- If the system fails, how important is it that workers understand why the system fails and how to solve it? Why?

- How compatible will the system be to other systems used within mining?

7.2 Interview Guide Case Study

Two types of interview guides were used: one for operators and one for managers and professionals. While both were adapted to the role of the informant, they differed in their main focus, reflecting the distinct perspectives of the two groups. Both guides are presented here. The questions have not been translated from Swedish into English, as the majority of interviews were conducted in Swedish.

Operator Interviews

- Hur länge har du arbetat här?

- Vad gjorde du innan? Och hur såg en typisk arbetsdag ut?

- Hur ser ditt arbete ut idag? (Berätta och beskriv i detalj hur en typisk arbetsdag kan se ut).

- Hur är dina tankar om din tjänst? (Brister, förtjänster, utvecklingspotential).

- Är arbetet stimulerande, innebär möjligheter till lärande och utvecklande? Berätta och beskriv hur, varför/varför inte.

- Hur skulle du beskriva att arbetet som [yrkesroll] är organiserat? Vem gör vad, vem delegerar arbetet? Hur funkar detta enligt dig?

- Vilka är dina ansvarsområden som [yrkesroll]? Och hur går dina tankar kring detta?

- Vad tycker du om AHS? (Brister, förtjänster, utvecklingspotential).

- Hur tror du att arbetet kommer förändras till följd av AHS? På kort och lång sikt?

- Hur funkar arbetet tillsammans med [andra yrkesroller]?

- Hur upplever du dina förutsättningar att påverka din framtid inom företaget?
- Hur upplever du dina förutsättningar att påverka det dagliga arbetet med det nya AHS?
- Vad tror du om framtiden? Hur kommer det att se ut om 10 år?

Management and Related Roles Interviews

- Hur länge har du arbetat här?
- Vad gjorde du innan du började arbeta med AHS projektet?
- Vad går ditt arbete ut på? Övergripande.
- Vad är syftet och målet med projektet enligt dig?
- Hur har projektet fortlöpt hittills?
- Utmaningar framöver?
- Hur påverkar det nya systemet arbetet i din mening? Vad händer med arbetet som följd av AHS?
- Hur skulle du beskriva de organisatoriska förändringar som det nya AHS innebär?
- Vilka kunskaper/färdigheter och utbildning behöver framtidens gruvarbetare ha?
- Vilka utmaningar uppstår till följd av det nya systemet? Och hur hanterar man dessa? (tekniska, organisatoriska, och sociala utmaningar).
- Hur har AHS tagits emot av personalen i gruvan? Beskriv gärna.
- Hur tror du att implementeringen av systemet i kommer att fungera? Överlämningen till produktionen. Vad är utmaningar i din mening? Berätta och beskriv.
- Vad kommer tror du att du kommer göra efter projektet avslutats?
- Vad tror du om framtiden? Hur kommer det att se ut om 10 år?

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