



A maturity framework for autonomous solutions in manufacturing firms: *The interplay of technology, ecosystem, and business model*

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Abstract

Significant advancements within the fields of digitalization, electrification, and automation have enabled the development, testing, and implementation of increasingly advanced autonomous solutions. Current examples of industrial automation promise significant economic and sustainability-oriented benefits for industrial customers. Yet, implemented autonomous solutions have rarely advanced beyond ‘islands of autonomy’. Although enabling initial improvements in the efficiency and effectiveness of operations, they have not led to the systemic process improvements that fully integrated site-wide solutions can achieve. It is becoming increasingly clear that the major challenges in this shift extend beyond technology to focus on business transformation and ecosystem relationships. Yet, extant research offers few insights into these domains. There is a need to develop a business-focused maturity framework for autonomous solutions to contribute to a predominantly technical discourse and support equipment actors and their wider ecosystems in commercializing autonomous solutions. Thus, the purpose of this paper is *to investigate how industrial equipment manufacturers can align the development of technology, business models and ecosystem relationships for the advancement of autonomous solutions*. We build on case studies that include 32 interviews from four industrial equipment manufacturers and their extended ecosystems of customers and partners. We capture our findings in a three-level maturity framework for industrial autonomous solutions. This framework unwraps the attributes of each level from the perspectives of technical system development, ecosystem configuration, and business model design and is complemented by three overarching principles for the successful commercialization of autonomous solutions.

Keywords Autonomous solutions · Ecosystems · Business models · Digital servitization · Digitalization · Automation

Introduction

Industrial equipment manufacturers are facing a huge shift due to rapid technological development and innovation in the areas of automation (i.e. self-driving vehicles),

electrification (i.e. battery propulsion) and digitalization (i.e. data, connectivity, and analytics). Increased equipment automation is regarded as a critical step as it offers significant benefits including improved efficiency, productivity, safety, and sustainability (Parida et al. 2019), with improved precision and reduced operational variance providing more consistent outcomes (Darling 2011, p. 805). Indeed, rapid technological advancements under the fourth industrial revolution are redefining the pace and scope of change in processes, capabilities, and offerings, creating innovation opportunities through the digital servitization of industrial firms and their ecosystems, which is reflected in a transition from product to service provision (Kamalaldin et al. 2020; Sjödin et al. 2020a). Improved communication and connectivity through the proliferation of IoT (Internet of Things) devices, cloud computing, and big data are pushing the development of digitally enabled services (Hasselblatt et al. 2018; Paiola and Gebauer 2020; Paschou et al. 2020). Physical products are being integrated into software systems and services to deliver higher levels of operational capability (Kohtamäki et al. 2019). Autonomous vehicles are an example of a digitally enabled service, where a wide array of sensor, communication, and computational resources complemented by new business services are being integrated to enable autonomous operation.

The development of autonomous solutions is transforming operations in a variety of industrial equipment sectors ranging from mining and forestry to construction and farming. Yet, despite the benefits of higher levels of automation (i.e. self-driving), autonomous solution development has largely been restricted to operator-assist functionalities. Higher levels of automation maturity with no operators exist primarily as ‘islands of automation’, operating in tightly compartmentalized areas of production with little or no interaction with external interfaces. Although they have enabled initial improvements in the efficiency and effectiveness of specific processes, autonomous solutions have not led to the systemic improvements that only fully integrated autonomous solutions can achieve (Darling 2011, pp. 805–806). Successful innovation of site-wide solutions will not only require resolution of numerous technical challenges but also the development of business models that align and incentivize ecosystem actors (Kohtamäki et al. 2019; Leminen and Wendelin 2018) to convert the technology potential of higher levels of autonomous operation into market outcomes (Pfeiffer et al. 2017). This is a critical step in one of more advanced aspects of digital servitization. For example, fully autonomous industrial solutions whose performance is pre-programmed and, therefore, predetermined by equipment suppliers requires a redefinition of traditional customer–supplier roles through the development of mutually beneficial revenue models that reflect new risk ownership arrangements. Engaging in this transformation is not easy, and many manufacturers struggle to realign their ecosystems and advance towards higher levels of automation maturity. There is a need for a clearer understanding of commercialization for different levels of automation on a scale that recognizes the variation in autonomous solution capabilities. The development and implementation of digitally enabled services such as autonomous vehicles are complex challenges requiring the management of multiple aspects extending beyond the purely technical domain. Yet, there is limited research associated with the business challenges of autonomous solutions, leaving several important gaps in knowledge related to commercializing autonomous solutions at different levels of maturity. Specifically, we identify three research gaps.

Firstly, there is a *need to consider the business model elements for advancing levels of autonomous solution maturity*. Prior research identifies the need for alignment between the value-capture, value-delivery, and value-creation components of the business model and the wider ecosystem (Ritter and Lettl 2018). Yet, limited studies have addressed these issues in the context of autonomous solutions. Revenue models must focus on fulfilling customer needs through incentivizing behaviors that encourage desirable outcomes, typically requiring a transition to outcome-based contracts (Lerch and Gotsch 2014, 2015) or alternative models where the usage or performance is charged to the customer (Parida et al. 2019). Closely coupled to the revenue model are the ownership arrangements, which, for higher levels of autonomous-solution maturity, change from a traditionally fully owned customer solution to a customized, hybrid arrangement where responsibility and risk are shared with suppliers. Despite the generally accepted understanding that more advanced digital solutions will likely require a move to outcome-based contracting, the case of autonomous solutions has not been tested and gaps in understanding remain as to how revenue models develop in relation to autonomous solution maturity.

Secondly, there is a *need to extend the understanding of autonomous solutions beyond the boundaries of a single firm to incorporate an ecosystem perspective*. Indeed, ecosystems connecting customers, suppliers, competitors, and partners are critical in order to profit from digitalization (Parida et al. 2019). For example, previous studies highlight the need for greater ecosystem collaboration and business model innovation in support of the transition to delivering increasingly advanced services (Kohtamäki et al. 2019; Leminen and Wendelin 2018; Luz Martín-Peña et al. 2018; Parida et al. 2019). The increased levels of system integration required to deliver more advanced automation necessitates a diverse and varied breadth of ecosystem partners (Iansati and Lakhani 2014; Pagani and Pardo 2017; Parida et al. 2019), each with their own special capabilities orchestrated in an interaction logic where a focal and orchestrating actor guides the other members (Perks et al. 2017). Higher levels of autonomous-solution maturity will, in addition, require a more open and transparent approach to data sharing in order to enable system innovation (Sjödinet et al. 2018). For example, the collaboration between Sandvik, Newtrax and IBM has been instrumental in the successful innovation of Sandvik's AutoMine system for autonomous mine operations (Rask 2017). However, it is not clear how the ecosystem configuration advances with the level of autonomous solution maturity, nor how the ecosystem is more broadly related to technology development.

Finally, there is a *need for a maturity framework to advance understanding of how firms can successfully develop and commercialize autonomous solutions*, taking into consideration the importance of alignment between technological, ecosystem, and business model perspectives. Current classifications of autonomous solutions within the digital servitization literature fail to capture the significant nuances between solutions at varying levels of technical complexity and purpose of application. Only abstract classifications state that autonomous solutions exist at the higher end of a linear digitalization capability scale (for examples, see Kohtamäki et al. 2019; Parida et al. 2019; Porter and Heppelmann 2014). This coarse differentiation fails to explicitly consider, for example, automated solutions operating with partial or semi-autonomous functionalities, overlooking the majority of industrial-use cases. The development of a maturity framework that clearly differentiates different autonomous

solutions will, therefore, facilitate the positioning of autonomous solutions and serve to support the decision-making activities of industrial actors seeking to commercialize autonomous solutions (Jin et al. 2014; Neff et al. 2014; Rapacciniet al. 2013; Sjödin et al. 2018).

To address these gaps, we developed the following research question: *How can industrial equipment manufacturers align the development of technology, business models and ecosystem relationships for the advancement of autonomous solutions?* To answer this question, we build on insights drawn from interviews with 32 informants from multiple case studies in four industrial equipment manufacturers in Sweden that are engaged in the development and provision of autonomous solutions. Our findings show that key activities are split across the three dimensions of technology development, ecosystem configuration, and business model design that evolve over three maturity levels of autonomous solutions (level 1: operator assistance, level 2: semi-autonomous operation, level 3: fully autonomous operation). By doing so, this study contributes to the digital servitization literature in three principal ways. Firstly, the study contributes through the development of a multi-dimensional maturity framework. Secondly, it advances understanding of the interplay between technology development, ecosystem configuration, and business model design for the commercialization of autonomous solutions. Third, it develops the existing digital servitization literature with a specific focus on exploring the context of autonomous solutions, providing related empirical insights.

The paper starts by providing a theoretical foundation on digital servitization and autonomous solutions, including an introduction to the development of a maturity framework. Following this, the study methodology is provided, describing how the data was collected and analyzed. The paper continues with a presentation of the findings, structured according to the three levels of maturity that are subsequently synthesized into a *framework for commercializing autonomous solutions*. The paper concludes with a discussion of the theoretical and managerial implications.

Theoretical background

Digital servitization and autonomous solutions innovation

Advancements in digital technologies have enabled manufacturing firms to transition from product to service provision (Adrodegari and Saccani 2017; Ardolino et al. 2018; Hasselblatt et al. 2018; Kohtamäki et al. 2019; Rust and Huang 2014). In other words, digitalization has changed how a company creates and captures value through greater provision of services (Iansati and Lakhani 2014). Consequently, the provider takes on greater responsibility for its customer's operational processes (Lerch and Gotsch 2015) by leveraging digital technologies in order to differentiate itself from competitors (Opresnik and Taisch 2015) and create new revenue streams (Scherer et al. 2016). This trend is referred to as 'digital servitization', which is defined as "transformation in processes, capabilities, and offerings within industrial firms and their associated ecosystems to progressively create, deliver, and capture increased service value arising from a broad range of enabling digital technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), and cloud computing" (Hasselblatt et al. 2018;

Paiola and Gebauer 2020; Paschou et al. 2020; Sjödin et al. 2020a, b). Hence, digital servitization encompasses the utilization of digital tools in order to make the transition from product-centric to service-centric business models (Sklyar et al. 2019b).

Digital servitization literature defines autonomous solutions as the most advanced form of digital servitization capability, starting with remote monitoring and then moving on to control and optimization before reaching autonomous solutions (Kohtamäki et al. 2019; Porter and Heppelmann 2014). Although the potential of autonomous systems to reshape industry has been recognized (Porter and Heppelmann 2014), autonomous solutions have largely been treated as an abstract conceptualization existing at the higher end of a linear digitalization capability scale (for examples, see Kohtamäki et al. 2019; Parida et al. 2019; Porter and Heppelmann 2014). This has resulted in confusion and lack of clarity when referencing autonomous solutions. For example, terms such as ‘autonomous harbor’ can be interpreted to mean either a system-of-systems solution with no human operator oversight of the majority of harbor operations or, conversely, as in this specific case, it is used to describe a set of disparate harbor activities with varying levels of monitoring, control, and optimization capabilities (for examples, see Grubic 2018; Kohtamäki et al. 2019). For clarity and consistency, we follow Darling’s definition of the term ‘autonomous’ as the ability of systems to function and make decisions independently of human supervision, and ‘automation’ as the umbrella term for tasks completed by machines that lack the capacity to make decisions (Darling 2011, pp. 805–806).

Although autonomous solutions have largely been treated at a more abstract conceptual level in the digital servitization literature, the work of Porter and Heppelmann has added greater technical nuance. Autonomous solutions are an example of smart, connected products that are radically changing the roles of traditional manufacturers and redefining industry boundaries (Porter and Heppelmann 2014). Smart, connected products are composed of three core elements: physical components, smart components, and connectivity components. Physical components represent the mechanical and electrical hardware, smart components encompass the computational capabilities, and connectivity refers to the wired or wireless communication to the product (Porter and Heppelmann 2014). Three levels of connectivity, from low to high, are defined for smart, connected products – one-to-one, one-to-many and many-to-many (Porter and Heppelmann 2014). Higher levels of solution connectivity enable increased operational performance through the leveraging of multiple system capabilities. It can, therefore, be expected that the more complex the autonomous solution, the higher its level of connectivity will be. Although Porter and Heppelmann’s framework offers important insights into smart, connected products, little differentiation is provided on varying levels of autonomy and how to advance to higher levels of solution maturity.

Towards a maturity framework for autonomous solutions

The development of an autonomous solution maturity framework has the potential to guide organizations that are managing their transformation to fully autonomous solutions by providing insights into the level of maturity. Assessing against a maturity model enables an “evaluative and comparative basis for improvement” across a range of dimensions determined by the domain of interest (de Bruin et al. 2005). A maturity model “represents an anticipated, desired or typical evolution path” from low to high

maturity across a series of sequence steps (Becker et al. 2009). Maturity models have been developed across a number of domains including IT, quality, project, and process management (de Bruin et al. 2005). However, we find no model that attempts to define autonomous-solution maturity for heavy equipment manufacturers. We argue that this is an important gap in understanding the appropriate configuration for autonomous solutions, which needs to account for different technical complexities and areas of application.

The automotive sector has defined a taxonomy of on-road vehicle automation consisting of six levels of driving autonomy (SAE International 2013):

- Level 0 – No driving automation
- Level 1 – Driver assistance
- Level 2 – Partial driving automation
- Level 3 – Conditional driving automation
- Level 4 – High driving automation
- Level 5 – Full driving automation

This taxonomy presents a useful hierarchy of automation, which can be applied to the off-highway industrial sectors by replacing the term ‘driving’ with the term ‘operation’ and considering the specific-use case of the automated machine (Frank 2019). Similar to how actors in the aviation industry have modified the automotive taxonomy applying to automation in an avionics context (Anderson et al. 2018), for equipment manufacturers, the levels of autonomous-solution maturity need to encapsulate the unique conditions and challenges associated with the innovation of autonomous solutions in this context. This will help to ensure consistency in application and interpretation, avoiding potential miscommunication and ‘overselling’ of autonomous capabilities in the servitization literature. It also serves to provide a baseline from which relevant and actionable steps can be taken to improve the level of autonomous-solution maturity.

In order to support the development of a maturity framework, themes of interest against which autonomous solution maturity can be assessed must be identified (de Bruin et al. 2005). Table 1 provides examples of autonomous-solution themes contained within the digital servitization literature. The review is not systematic or exhaustive; however, the lack of articles is a fitting illustration of the limited attention that autonomous solutions have thus far received. Notably, there is, to the best of our knowledge, no single paper explicitly focused on innovation and commercialization of autonomous solutions in the literature. The importance of business models and the value of an ecosystem perspective for advanced technology development are consistent themes highlighted across the articles; see Table 1.

Technology development for autonomous solutions

The continual improvement and growing availability of digital technologies is pushing the development of autonomous solutions by replacing tasks previously dependent on human operators with a collection of integrated systems capable of executing their own decisions and taking independent action. Enabling technologies such as AI, IoT, and cloud computing are advancing the possibility of integrating the different systems that autonomous solutions require to create a systems-of-systems integration (Frank 2019).

Table 1 Examples of autonomous solution themes contained in the digital servitization literature

| Authors, Year | Title | Autonomous Solution Themes |
|-----------------------------|---|---|
| Kohtamäki et al. 2020 | The relationship between digitalization and servitization: the role of servitization in capturing the financial potential of digitalization | The role of digitalization as an enabler of advanced services such as autonomous solutions is described. In addition to digital technologies, a transition to advanced services requires new organizational processes and resources |
| Tronvoll et al. 2020 | Transformational shifts through digital servitization | A transition to digital servitization must extend beyond a merely technical focus to also consider collaboration in multi-actor partnerships, effective management of data, and a change in organizational identity focused on service centricity |
| Kohtamäki et al. 2019 | Digital servitization business models in ecosystems: A theory of the firm | The interrelationship between business models and ecosystems in digital servitization is conceptualized. A three-dimensional framework classifies five different digital servitization business models, with autonomous solutions defined as the highest level of solution digitalization |
| Parida et al. 2019 | Reviewing literature on digitalization, business model innovation, and sustainable industry: past achievements and future promises | Autonomous solutions considered to be an advanced form of digital servitization. The ability to deliver advanced digital servitization reliant on business model innovation within an ecosystem of actors |
| Sklyar et al. 2019a | Resource integration through digitalization: a service ecosystem perspective | Digital technologies both increase pattern complexity within ecosystems but also serve to facilitate management of that complexity. Connecting ecosystem actors helps them successfully leverage the benefits from new technological opportunities |
| Hasselblatt et al. 2018 | Modelling manufacturers capabilities for the Internet of Things | A capability model for the delivery of IoT solutions is presented. Importance of ecosystem management in generating and capturing value is highlighted, alongside a required shift in focus from product to value selling |
| Leminen et al. 2018 | The future of the Internet of Things: toward heterarchical ecosystems and service business models | Business model and ecosystem perspectives are used to investigate digital servitization in manufacturing (focus on IoT). Process decomposition effects of connected technologies linked to development of new business model configurations |
| Luz Martín-Peña et al. 2018 | The digitalization and servitization of manufacturing: A review of digital business models | Systematic literature review explores digital business models. Cyber-physical systems linked to development of autonomous ecosystems |

Table 1 (continued)

| Authors, Year | Title | Autonomous Solution Themes |
|----------------------------|---|---|
| Sjödin et al. 2018 | Smart factory implementation and process innovation – a preliminary maturity model for leveraging digitalization in manufacturing | A maturity model for the development of a smart factory is provided. Autonomous solutions identified as an important component of smart factory implementation |
| Porter and Heppelmann 2015 | How smart, connected products are transforming companies | Investigation into the role of smart connected products in transforming manufacturing firms. Development of smart connected products linked to evolution of autonomous systems |
| Porter and Heppelmann 2014 | How smart connected products are transforming competition | Autonomy defined as the most advanced capability of smart connected products. Strategic choices that companies need to make in order to gain competitive advantage in the context of smart connected products are provided |
| Paiola et al. 2013 | Moving from products to solutions: Strategic approaches for developing capabilities | The study highlights the strategic options available to companies in the delivery of integrated solutions, ranging from internal to external and combinations in between – highlighting the importance of ecosystem dynamics as a |

Yet we still lack a common frame of reference for classifying different levels of autonomous solution maturity, with the digital servitization literature applying the same terminology for solutions with significant variance in technical complexity and area of application. Despite the central role of technology, innovating autonomous solutions requires the focus to be shifted so that ecosystem and business model features are also considered.

Ecosystems for autonomous solutions

The development of autonomous solutions challenges equipment manufacturers to work across firm boundaries and consider a wider ecosystem of actors, systems, and products (Parida et al. 2019). The term ‘ecosystem’ has been borrowed from biology, and management scholars generally use it to refer to a group of firms that interact and depend on each other’s activities. Researchers have identified three streams that define an ecosystem differently (Jacobides et al. 2018). These are the ‘business ecosystem’ stream that focuses on a particular firm and its surrounding environment and organizations, the ‘platform ecosystem’ stream that focuses on a platform and how different actors organize around it, and the ‘innovation ecosystem stream’ that focuses on a focal innovation or value proposition and the set of actors that support it. The innovation ecosystem view, which this paper adopts, defines an ecosystem as “collaborative arrangements through which firms combine their individual offerings into a coherent, customer-facing solution” (Adner 2006, p. 98). This view focuses on understanding how different actors interact to co-create and commercialize innovations, capturing “the

link between a core product, its components, and its complementary products/services” that jointly add value to the end customer (Jacobides et al. 2018, p. 2257). The “dispersed nature of specialized knowledge and the networked nature of technology development” means that firms must innovate collaboratively (Ritala et al. 2013; Sjödin et al. 2019). Digitalization is recognized as a key factor in the distributed nature of specialized knowledge due to the effect of decoupling “information from the devices and technologies that can potentially reshape the nature of service activities” (Sklyar et al. 2019b). Firms must, therefore, shift their focus from a traditional product orientation to consider smart and connectivity components (Porter and Heppelmann 2014). This not only serves to improve product capabilities from monitoring, control, optimization, and autonomy perspectives but also changes fundamentally the nature of relationships with other industrial actors. To truly leverage the benefits of increased connectivity and enable a system-of-systems approach, equipment manufacturers must seek to strengthen their autonomous solutions through connectivity to complementary system capabilities from other ecosystem actors “beyond firm boundaries and across networks in the form of collaborative value creation” (Parida et al. 2019), including possible collaboration with competitors (Iansati and Lakhani 2014). However, how to achieve this transition is not well understood in theory or practice. In addition, companies that ignore this inevitable transition “may find their traditional products becoming commoditized or may themselves be relegated to the role of OEM supplier, with systems integrators in control” (Porter and Heppelmann 2014). The technology development of autonomous solutions must, therefore, be complemented by active management of the ecosystem configuration to ensure that effective collaboration takes place and that the potential for innovation is suitably enhanced.

Business models for autonomous solutions

Alongside the technical and ecosystem perspectives, organizations need to develop an effective business model design that considers the sub-component implications of value delivery, value creation, and value capture (Linde et al. 2021; Parida et al. 2019). Each of these dimensions must be addressed and aligned with the overall business logic of the company to ensure development of an effective business model strategy (Ritter and Lettl 2018). Aligning the business model to other ecosystem actors with regard to the routines, technologies, value propositions, and pricing logics is called ‘strategic fit’ (Kohtamäki et al. 2019). Strategic fit recognizes that, as firms develop their digital servitization business models, they will be dependent on the complementary capabilities of other actors within the ecosystem (Kohtamäki et al. 2019). Due to the radically different nature of autonomous solutions to standard product sales, this can be a paramount challenge for manufactures resulting in misaligned business models. Misalignment of the business model can result in missed opportunities or conflicting design elements, leading to value leakages (Parida et al. 2019; Sjödin et al. 2020b). Moreover, it is plausible that the business model would need to change as companies progress towards the commercialization of increasingly higher levels of automation. Yet, these dynamics are less understood.

Although the existing literature supports our understanding of the importance of interaction between technology, ecosystems, and business models, it is clear that there

is much that needs to be studied on their specific relation to autonomous systems. There is a specific need to investigate appropriate configurations of autonomous solutions at different maturity levels in order to understand the commercialization challenges that industrial actors face.

Methods

Research approach and case selection

The present study is built on exploratory multiple case studies (Yin 2018) of four industrial equipment manufacturers based in Sweden, and their extended ecosystems of partners and customers. The case-study methodology enables us to mobilize multiple observations on complex relational processes (Eisenhardt 1989; Eisenhardt and Graebner 2007), which is especially suitable for developing new insights into theoretically novel phenomena (Edmondson and Mcmanus 2007). This leads us directly to the research question: *How can industrial equipment manufacturers align the development of technology, business models and ecosystem relationships for the advancement of autonomous solutions?*

The cases for this study were selected by theoretical sampling (Eisenhardt 1989; Eisenhardt and Graebner 2007; Glaser and Strauss 1967), and the selection criteria were informed by the study's purpose (which was to develop a maturity framework for industrial autonomous solutions, focused on the perspective of industrial equipment manufacturers). The study's purpose captures three key aspects: the perspective of industrial equipment manufacturers, the context of autonomous-solutions provision, and the focus on maturity-level development of these solutions. Consequently, the case selection criteria are as follows.

First, we selected large industrial equipment manufacturers in Sweden, with which we had established good contacts due to the ongoing nature of the research project. The selected manufacturers are all developing industrial solutions for industries such as mining and construction. These industries are typically associated with high capital costs invested by the manufacturer and, thus, purchasing its products requires a sizable investment by the customer. This emphasizes the special nature of the strategic engagement between the equipment manufacturer and other actors in its ecosystem, including the customer and digitalization partners. Therefore, although the present study focuses on the perspective of the equipment manufacturers, we found it important to consider other ecosystem actors in order to understand the ecosystem configuration and the business model design. Hence, having access to the data of other ecosystem actors, alongside the equipment manufacturer, was a key case-selection criterion. This made for rich data collection and allowed us to gain a deeper understanding of the ecosystem configuration and the interactive relationships between multiple actors.

Second, we selected cases where the equipment manufacturer is actively involved in the provision of solutions as opposed to solely providing products. All the selected cases are undergoing a transformation from product-centric models to service-oriented solution offerings, to one degree or another. This enabled us to explore the different business models associated with different offerings of autonomous solutions.

Third, we selected equipment manufacturers that are either developing, testing, and/or implementing a range of autonomous solutions at different autonomous maturity levels. These range from operator-assisted functionalities to semi-autonomous solutions minimizing operator workload, and on to the development of fully autonomous solutions with no human operator. This range of autonomous solutions, and the correlated technology development, facilitated a comparison between different maturity levels and, thus, supported the development of a maturity framework.

Data collection

Data for the present study were collected through individual semi-structured interviews with informants from the four case manufacturers, as well as informants from other actors in the associated ecosystems. Key informants from the case manufacturers were selected due to their involvement in the development and provision of autonomous solutions. Additional informants were identified using a snowballing technique, where key informants were asked to recommend other people who could offer additional insights for the study. In total 32 interviews across 10 companies have been conducted, out of which 11 interviews focused more specifically on themes related to autonomous solutions. The remaining interviews from an earlier project phase contribute to an enhanced understanding of the wider phenomena of autonomous solutions and digitalization, enabling the subsequent study direction and formation of the framework. The interviewees include representatives from the equipment manufacturing companies themselves, in addition to informants from their customer and partner companies. In order to capture a wider understanding from different organizational perspectives, we interviewed informants exercising various functional roles in these companies. Table 2 provides an overview of the companies and the positions of interviewed informants.

Company informants were asked open-ended questions. This was facilitated by an interview guide, which was based around overarching themes such as the development and implementation of autonomous solutions, data and technology, ecosystem collaboration and competition, and business model design. Examples of interview questions include: *‘What examples of autonomous solutions do you develop/provide/procure?’*, *‘What are the most significant challenges in implementing higher levels of autonomy?’*, *‘What technologies and capabilities are needed to implement autonomous solutions?’*, *‘Who are the key ecosystem partners and how would you describe the relationships between them?’*, *‘What contracting arrangements are being used?’*, *‘How can different business models be configured?’*. Follow-up questions were asked in order to obtain further details or clarification. It is worth mentioning that the interview guide was continuously revised as new insights were gleaned from the collected data. Interviews lasted between 45 and 90 min each, and all were recorded and transcribed. Interview transcripts provided the primary basis for data analysis.

Data analysis

A thematic analysis approach was adopted to analyze the data and identify relevant themes and patterns (Braun and Clarke 2006). Through a series of iterations and comparisons, themes and overarching dimensions were identified from the data, which enabled the development of an empirically grounded framework. To be

Table 2 Overview of the case companies and informants

| Company Pseudonym | Industry | Revenues / Employees | Informants |
|--------------------------------|--|--------------------------|---|
| <i>Equipment Manufacturers</i> | | | |
| Rockcorp | Mining equipment & infrastructure | SEK 41 billion / 14,000 | <ul style="list-style-type: none"> • Automation Product Portfolio Manager • Automation Global Product Line Manager • Digital Service Transformation Manager • Business Development Manager |
| Equipmentcorp | Construction & mining equipment | SEK 100 billion / 43,000 | <ul style="list-style-type: none"> • Automation Global Business Development Manager • Automation Business Line Manager • Underground Automation Product Line Manager |
| Constructcorp | Construction equipment & industrial machinery | SEK 48 billion / 14,000 | <ul style="list-style-type: none"> • Product Planning & Services Manager • Connected Site & Machine Services Manager • Technology Planning Manager |
| Autocorp | Automotive | SEK 137 billion / 52,000 | <ul style="list-style-type: none"> • Autonomous Solutions Director • Automation Solutions Manager • Connected Services Manager • Intelligent Transport Systems Manager |
| <i>Digitalization Partners</i> | | | |
| Solutioncorp | Industrial digital solutions and engineering | SEK 152 million / 90 | <ul style="list-style-type: none"> • Chief Technology Officer • Business Development Manager |
| Connectcorp | Digital hardware & software, cloud computing, AI | SEK 7 billion / 1,500 | <ul style="list-style-type: none"> • Industrial Sales Manager • IoT Consulting Services Manager |
| Digitalcorp | Digital hardware & software, cloud computing, AI | SEK 5 billion / 500 | <ul style="list-style-type: none"> • Cloud & AI Business Development Manager • AI Solutions Sales Manager |
| <i>Industrial Customers</i> | | | |
| Minecorp | Mining | SEK 50 billion / 6,000 | <ul style="list-style-type: none"> • Chief Procurement Officer • Chief Information Officer • Mine Automation Program Manager • Mine Technology Section Manager • R&D Manager • IT Manager |
| Ironcorp | Mining | SEK 26 billion / 4,000 | <ul style="list-style-type: none"> • Chief Procurement Officer • Supply Chain Manager • R&D Manager • Project Manager |
| Forestcorp | Forestry | SEK 21 billion / 4,000 | <ul style="list-style-type: none"> • Chief Technology Officer • R&D Manager |

specific, a three-step process was followed, guided by Gioia et al. (2013). Firstly, interview transcripts were read, and key terms from informants coded, resulting in first-order concepts that reflect the views of informants. Secondly, patterns within the

first-order concepts were identified through an iterative process, which led to the development of nine second-order themes that were on a higher level of abstraction than the first-order concepts. Thirdly, aggregate dimensions that are on the highest level of abstraction were generated. Following the approach of Gioia et al. (2013), insights from the literature were used to guide the development of labeling that is both theoretically and empirically grounded. Fig. 1 shows the data structure that resulted from the data analysis. Finally, the findings that emerged from data analysis were synthesized into a maturity framework of three maturity levels of autonomous solutions (level 1: operator assistance, level 2: semi-autonomous operation, level 3: fully autonomous operation).

Findings: detailing a maturity framework for autonomous solutions

In this section, we present the basis for a maturity model for autonomous solutions provision that emerged inductively, based on an analysis of the four cases studied. We

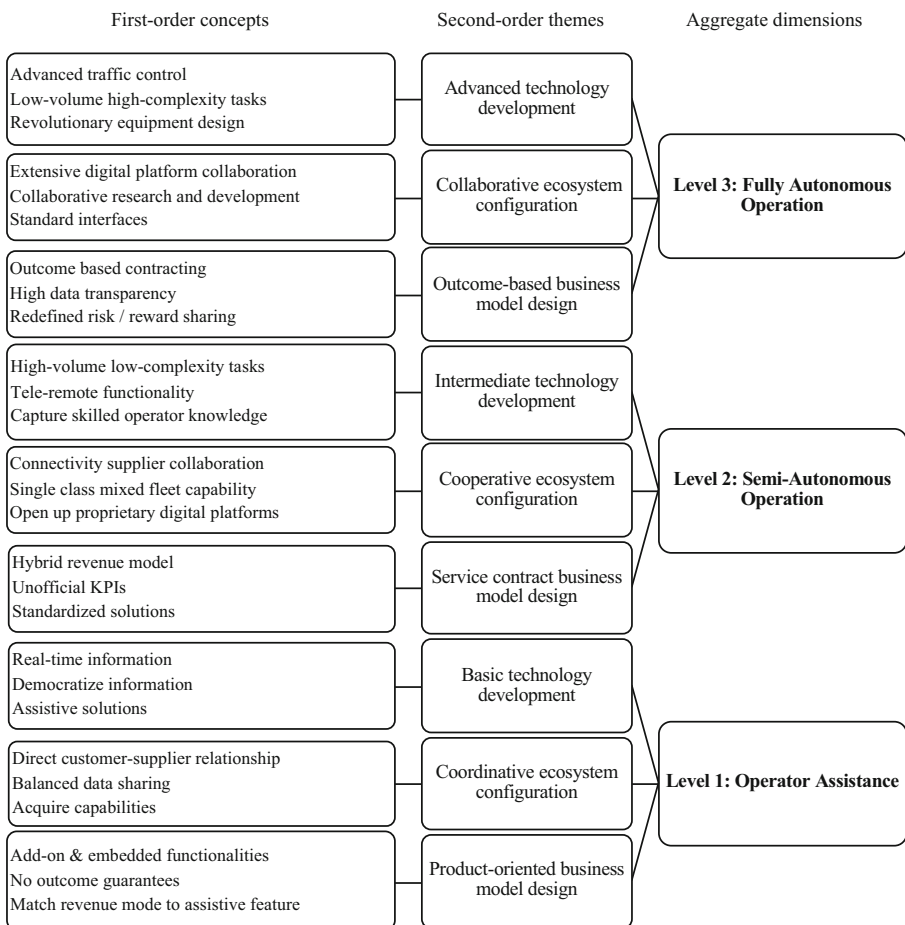


Fig. 1 Data Structure

present our findings in three parts, each corresponding to one of the three maturity levels that emerged from the analysis: 1) Operator assistance, 2) Semi-autonomous operation and 3) Fully autonomous operation. Key to our findings, summarized in Table 3, is the interdependence between technical system development, ecosystem configuration, and business model design for successfully advancing to a higher level of maturity Table 3.

Maturity level 1. Operator assistance

The lowest level of autonomous-solution maturity is referred to as ‘operator assistance’. At this maturity level, the operator maintains full operational control of the equipment but is assisted by component and sub-system automation, such as an automatic gearbox or collision avoidance system. Assistive real-time information can also be provided to the operator to improve situational awareness and aid decision making. Although, at the lowest level of maturity, the automation solutions at Level 1 are an important part of the technology mix in the two subsequent stages of maturity.

Technology development Development efforts are focused on operator-assist functionalities, which either enhance situational awareness through the provision of real-time assistive information aiding decision-making capabilities or minimizes the operator burden through automation of previously manual operator tasks. Automation is, therefore, operator-centric, simplifying and reducing the operator workload. An automation customer confirmed the importance of operator-assisted functionalities and stressed that their continued development remains a key focus for achieving higher levels of autonomous equipment maturity, specifically referencing collision-awareness and collision-avoidance systems. The provision of digitally enabled situational awareness systems should democratize information and support the development of “distributed knowledge” throughout the workforce, achieving a multiplier effect of efficiency and effectiveness benefits. To illustrate, a supplier commented that information democratization provides an “information advantage” to make better decisions and can lead to significant safety and process improvements.

Ecosystem Configuration The extent of ecosystem collaboration required to deliver operator-assist functionalities is dependent on both the technical understanding of the assistive solution and its capacity to act in isolation from other systems. When delivering mature, well-understood and stand-alone solutions, relatively low complexity means that little consideration needs to be given to involving a wider ecosystem of actors. For example, the inclusion of an automatic gearbox in underground mining equipment does not require a coordinated effort with external stakeholders; the technology is simply embedded in the machine and requires no further integration into external systems.

The manufacturer often collaborates or acquires external expertise in order to support the development of novel digital technologies. Incorporation of novel digital technologies beyond the traditional expertise of equipment manufacturers will likely require collaboration with external suppliers. In order to capitalize on SME success, large mining equipment manufacturers have been acquiring access to digital systems from specialist SMEs through acquisitions to provide navigation guidance and assistive

Table 3 A maturity framework for autonomous solutions

| Maturity Level | Technology Development | Ecosystem Configuration | Business Model Design |
|---|--|---|--|
| <p>Level 3: Fully Autonomous Operation</p> <p>Operating independently of human control and capable of ‘learning’, optimizing operations and handling mission deviations</p> | <ul style="list-style-type: none"> Enhance equipment decision and optimization capabilities through the deployment of AI and sensor-based technologies – targeting low-volume and high-complexity tasks within the operational cycle Implement advanced traffic control capabilities to enable the safe and ‘fenceless’ operation between multi-brand and multi-fleet solutions, with human, manual, and autonomous equipment operating side-by-side Adopt a revolutionary approach to equipment design tailored to autonomous operation – removing the requirement for traditional human operator interfaces | <ul style="list-style-type: none"> Evolve digital platform capabilities to manage mixed fleets of multi-class equipment through collaboration with other equipment suppliers Accelerate autonomous solution scaling through collaborative ecosystem research & development initiatives Implement and refine standard interfaces to increase the potential for platform consolidation and collaboration | <ul style="list-style-type: none"> Implement outcome-based contracting to incentivize shared goals Utilize data transparency for auditability and trust in measuring solution performance Redefine risk/reward sharing arrangements to reflect outcome-based revenue model |
| <p>Level 2: Semi-Autonomous Operation</p> <p>Semi-autonomous solution with remote operator oversight, streamlines operational activities, minimizes operator burden, and improves safety</p> | <ul style="list-style-type: none"> Implement tele-remote technologies to minimize the requirement for on-site operator control and its associated risks Develop semi-autonomous operation capabilities for high-volume and low-complexity tasks within the operational cycle through the implementation of AI and sensor-based technologies Capture skilled operator knowledge within the autonomous solution to mitigate the loss of expertise | <ul style="list-style-type: none"> Leverage ecosystem capabilities by opening up proprietary digital platform (APIs) Develop digital platform capabilities with other equipment actors to handle mixed fleets of equipment Seek collaboration with connectivity suppliers to develop solution compatibility and standardization | <ul style="list-style-type: none"> Implement hybrid revenue models combining one-off equipment purchases with software service licensing Develop trust using equipment insights to guide the customer with unofficial KPIs and performance guarantees Refine delivery processes by transition from one-off project deliveries to standardized solutions and platforms |
| <p>Level 1: Operator Assistance</p> | <ul style="list-style-type: none"> Develop operator-assisted functionalities through the | <ul style="list-style-type: none"> Direct supplier-customer relationship with limited involvement of | <ul style="list-style-type: none"> Support the customer in maximizing solution benefits without |

Table 3 (continued)

| Maturity Level | Technology Development | Ecosystem Configuration | Business Model Design |
|--|---|--|---|
| Automation technology augments solution to improve efficiency and operability for the operator | provision of real-time assistive information or automation of operator tasks • Design assistive solutions for continued reliance on human operator control and oversight • Democratize information flows to empower operators | other ecosystem actors for mature operator-assist technologies • Collaborate or acquire external expertise in order to support development of novel digital technologies • Balance data sharing arrangements between competition and collaboration | committing to performance guarantees • Deliver well established and understood assistive features through simple add-on or embedded functionalities • Match revenue model to assistive solution configuration |

functionalities for industrial equipment. The Chief Technological Officer from an SME supplier commented that development of the assistive solution will be tailored to meet the requirements of the equipment manufacturer, enhancing the value proposition for the end customer of the equipment through improved operator-assist functionalities.

Data sharing arrangements are found to be balanced between competition and collaboration. System interoperability requires more open data flows, which must be balanced with organizational interests. An industrial equipment customer commented on the importance of reaching a win–win arrangement between actors:

“How do you share data in a good way that you have a win–win situation. We don't want to, let's say, hide data from a supplier because we're not in competition. But, of course, to deliver data, we would like to have something back”.

Business model design At this level, the findings show that it is necessary to support the customer in maximizing the assistive solution benefits without committing to performance guarantees, thus resulting in business models that are more closely aligned with transactional as opposed to relational engagements. A key reason for this transactional approach is that the lack of manufacturer process control due to reliance on a human operator means that performance improvements can only be achieved through the proper use of the assistive solution and, therefore, cannot be guaranteed by the manufacturer. The revenue model is aligned to the assistive solution configuration, meaning that autonomous hardware components are included as part of the total unit price of the autonomous equipment, with license or subscription-based revenue models for software-enabled assistive services. Due to the assistive nature of the autonomous augmentation, assistive features are typically delivered as simple add-on or embedded functionalities that do not require extensive redesign or modification of the industrial equipment.

Maturity level 2. Semi-autonomous operation

Semi-autonomous operation is representative of a significant number of current industrial equipment automation initiatives. It encompasses semi-autonomous equipment operation, typically with a human supervisor conducting assisted tele-remote monitoring and control in the event of mission deviations. The semi-autonomous vehicle is capable of independently completing operations in clearly defined use cases. The focus of this maturity level is on automation of the machine.

Technology development Semi-autonomous conditional operation capabilities are primarily developed for high-volume and low-complexity tasks within the equipment operational cycle through the implementation of smart technologies. Mission-controlled vehicles are designed to perform a tightly bound and pre-defined use case, with remote operator standby and supervision in order to handle mission deviations and more complex process tasks through tele-remote operation. Examples of system implementation range from one operator monitoring and assisting one machine, to one operator managing multiple pieces of equipment but “each in their own production area”. In order to advance to the next level of maturity, further developments seek to extend this capability to one remote operator managing multiple pieces of equipment in the same production area, assisted by traffic-control oversight. A defining characteristic of semi-autonomous operation is that the equipment operates in sealed-off production areas, keeping manual and autonomous equipment separate, as well as removing the potential for human–machine interaction. As one senior automation manager confirmed: “We cannot mix manual traffic with autonomous traffic for safety reasons”.

The delivery of semi-autonomous capabilities requires a restructuring of roles and competencies in order to accommodate the technological shift towards greater equipment autonomy. The reduced requirement for machine operators is offset by a requirement to retrain and hire “more electricians...more IT people...more communication people”. This is complemented by reskilling existing operators to handle and manage assisted tele-remote operations. Equipment manufacturers also seek to capture skilled operator knowledge as a part of the autonomous solutions in order to mitigate the loss of expertise or competence. A section manager from a customer organization commented that “our operators today are still very skilled, but we are losing competence out in the mines”, with production staff more frequently changing roles in their careers. By capturing expert knowledge within the machinery, the risk of losing valuable know-how is mitigated.

Ecosystem Configuration Equipment manufacturers are found to collaborate with connectivity suppliers to develop solution compatibility and standardization. Interviewees confirmed that increased autonomous system complexity requires the development of new ecosystem collaborations and partnerships to complement existing ones. The importance of information management in implementing autonomous solutions led to a new collaboration between a leading equipment manufacturer working more closely with a connectivity supplier. In this example, connectivity standards were developed from close collaboration between the equipment manufacturer and the connectivity

supplier, resulting in the end customer receiving a networked solution tailored to the requirements of its autonomous equipment operations.

To enable greater ecosystem collaboration and to “capture a larger part of the mining cycle”, proprietary digital platforms developed under maturity level 1 may be opened through provision of access APIs. A senior representative from an end-customer organization confirmed that “it was much more proprietary before”. An equipment manufacturer respondent stated that “we have opened up the systems with an access API, which we can pretty much allow any OEM to connect to”. This enables the customer and equipment manufacturers to develop solutions to monitor mixed fleets of equipment – for example, mining haulage machines.

Although the less restricted platforms enable better insights to be obtained for a specific class of equipment, a respondent stated that there is still no overarching “interface to see your complete fleet”, which would enable “smarter analytics” and resolve the problems around “small islands of data”. Therefore, digital platforms benefit from being developed in collaboration with other ecosystem actors in order to handle mixed fleets of equipment. An industrial equipment respondent commented that third party suppliers are currently developing the ability to autonomously operate mixed classes of equipment.

In response to difficulties associated with the management of multiple digital platforms, some customers have “decided to build an overhead database system that can collect telemetric data from different subsystems”. Other customers highlight the organizational benefits of multiple digital platforms, aligning well with equipment workshops that are categorized according to brand.

Business model design At this level, a transition from one-off project deliveries to standardized solutions and digital platforms can lead to the refinement of delivery processes. The high cost of delivering unique and complex autonomous solutions drives equipment manufacturers towards offering standardized configurations. For example, a manufacturer confirmed that the initial delivery of semi-autonomous solutions was handled “within several really big [customized] projects”. Subsequent solution standardization improved delivery speed and enabled the equipment manufacturer to cater to growing demand.

Equipment manufacturers are found to employ hybrid revenue models combining one-off equipment purchases with software service licensing. Contrary to the academic view that higher levels of digital servitization are typically accompanied by a transition to outcome-based revenue models, respondents articulated a more conservative business response. A hybrid arrangement with capital expenditure for the semi-autonomous vehicle, accompanied by a licensing agreement for the automation solution was the standard arrangement. Service contracts and use contracts are avoided, with one equipment manufacturer stating that “we took the strategic decision not to sell this as a service because then we start competing with some of our largest customers who are contractors”. The equipment supplier viewed this as something that “is not what an equipment manufacturer should do, even though it makes quite a lot of sense in many cases”.

Manufacturers recognize the importance of developing trust and utilize equipment insights to guide the customer with unofficial KPIs and performance guarantees. Of

particular note was the comment from one respondent who stated that, although a mixed revenue model of capital expenditure and licensing was utilized, they closely collaborated with customers to produce expected returns from autonomous operation – unofficial KPIs that the solution must subsequently meet in order that a good customer relationship is maintained:

“Yes, in many ways it is, but we do have customers requesting more of operated types of deals. We had a customer quite recently who said, ‘Well, we know exactly what the system needs to do, and you have proven by studies’, because we often do that, we do studies where we look at what we expect the system to perform. Then, in that sense, we know the cost per ton, we know what our system is expected to deliver...of course, if we have made a study that shows them that this is what we expect to produce or this is what we expect this machine to produce with the system, of course, they're going to keep us responsible for that or they're going to hold us responsible for those numbers. If we don't perform, of course, they will come back to us and be quite displeased.”

Commenting on the transition to outcome-based contracts, a respondent from the customers' organization reflected that “we are not really seeing the OEM (Original Equipment Manufacturer) being attractive enough in their offering for a performance-based model”. The customer favors procurement of the autonomous software under licensing agreement and retaining ownership of performance outcomes.

Maturity level 3. Fully autonomous operation

Fully autonomous operation represents the final level of autonomous system development and, although some elements have been achieved by the respondents, not one has completed a full transition to this level. Equipment operating in this category is capable of completing pre-assigned missions, handling deviations, and learning from its operational environment. The focus of automation is on the process, and the solutions represent a system-of-systems integration, which negates the requirement for dedicated operator oversight.

Technical system development At this level, manufacturers will aim to enhance equipment decision and optimization capabilities through the deployment of AI and sensor-based technologies – targeting low-volume and high-complexity tasks within the operational cycle. A senior equipment automation manager commented that current semi-autonomous machines in the mining sector are unable to handle the variations in rock sizes resulting from blasting operations. Instead, a human operator working in assisted tele-remote operations takes over this function with the respondent commenting that:

“sometimes it's very hard to do this operation completely autonomously. This is something we are working on a lot, to use previous standards and AI to help the machine to take those decisions by themselves. That's coming shortly”.

Extending the influence of AI, machines operating at this level of autonomy will not only be capable of handling mission deviations but will also have the capability to learn and optimize the missions it performs:

“then with AI, the machine can actually start to understand a condition based on vibrations, based on its Y-axle movements and things like that. That’s also an example for how AI can be used, or machine learning can be used for optimizing the production cycles of the machine”.

Advanced traffic control capabilities will be required to enable the safe and ‘fenceless’ operation between multi-brand and multi-fleet solutions, with human, manual, and autonomous equipment operating side by side. The subsequent easing of restrictions and enhancement of capability will enable the revolutionary as opposed to the evolutionary design of autonomous vehicles, conceived specifically without the need for a human operator. However, a respondent highlighted the continuing need for flexibility in this endeavor:

“Of course, going forward in the future, when we can actually mix manual and autonomous traffic in a completely different way, well then suddenly the need for the cabin will be less and less over time. Today, I think flexibility... flexibility is very important. That’s the reason we are going to see the cabins on the machines for quite some time going forward.”

Ecosystem configuration Manufacturers will need to develop digital platform capabilities to manage mixed fleets of multi-class equipment through collaboration with other equipment suppliers. Ecosystem collaboration includes firms with specialist competencies in the development of advanced autonomous capabilities, with respondents confirming that higher levels of system complexity require broader collaboration. An equipment manufacturer stressed that complementarity is a key consideration when establishing new partnerships, as well as recognizing that “the more the solutions go digital and interface with different solutions, the greater the requirements for interoperability”. A consistent theme from respondents was the recognition that there is no “single player that would be very strong or extremely good at everything”. Equipment suppliers should, therefore, aim to implement and refine standard interfaces to increase the potential for digital platform consolidation and collaboration. *Equipment manufacturers* will likely engage in collaborative ecosystem research and development initiatives to accelerate autonomous solution scaling. One equipment manufacturer stated that the investment in research and development is so high that partnering with “other industries to maybe share the cost or reuse solutions and platforms” is a way to scale up solution development and implementation. Partnering for this manufacturer included collaboration with a neighboring ecosystem defense-system actor that had developed traffic management solutions, which could be modified to suit the operational environment of underground mining.

Digital platforms are expected to be increasingly open and consolidated around market-leading solutions that capture larger elements of the industrial process cycle, reducing digital overheads and supporting improved insights. Data sharing will become

increasingly open and transparent, with equipment manufacturers “developing more and more standard interfaces [to be] able to interact with other types of players”.

Business model design Manufacturers will move from hybrid revenue models towards outcome-based contracting, incentivizing shared goals and capturing the value from previously unofficial KPIs. Risk sharing is, therefore, redistributed amongst stakeholders, with a larger portion owned by the equipment suppliers. It is consequently important to redefine the risk–reward sharing arrangements to reflect the outcome-based revenue model. However, as reflected on by a senior equipment manufacturer respondent, a transition to outcome-based contracts is reliant not only on the parties involved having full access to all the required information, but also on complete transparency and trust in how outcome-based KPIs are measured – in essence, “the supplier [and customer] needs to feel at peace with daring to go into such a contract”. Data transparency should, therefore, be utilized for auditability and trust in measuring solution performance. A respondent from the customers’ organization further articulated the need for not only trust but also for shared value from outcome-based contracts, stating that:

“we need to feel confident that the price level is right, and that we get a sufficient part of the benefit”.

A framework for commercializing autonomous solutions

Based on the analysis, this research article proposes a framework to explain how providers and their customers can profitably commercialize autonomous solutions, see Fig. 2. The framework is grounded in empirically rooted and theoretically motivated themes and dimensions that emerged during the data analysis. The framework visualizes the three key dimensions (technology development, ecosystem configuration, business model design), evolving across the three autonomous solution maturity levels and interconnecting with the three overarching principles. We contend that the framework can serve as a foundational premise for the commercialization of autonomous solutions by highlighting that: *technology development needs to go hand in hand with ecosystem configuration and business model design.*

To successfully innovate autonomous solutions, manufacturers should consider the three principles that encapsulate the interconnections between the dimensions illustrated in the framework: technology, ecosystem, and business model. The principles provide overarching guidance and represent a short-hand summation of informant responses. These principles are *adapting technology to ecosystem maturity*, *aligning partner revenue flows*, and *identifying technological value generators*. They are described in detail below.

First, *adapting technology to ecosystem maturity* is an important consideration when developing autonomous solutions, requiring alignment between the complexity of the solution and the capability of the receiving organizations to manage that complexity. For example, customers need to have the requisite data management capabilities and digital maturity to handle the new ways of working with autonomous solutions. Similarly, manufacturers need to consider the

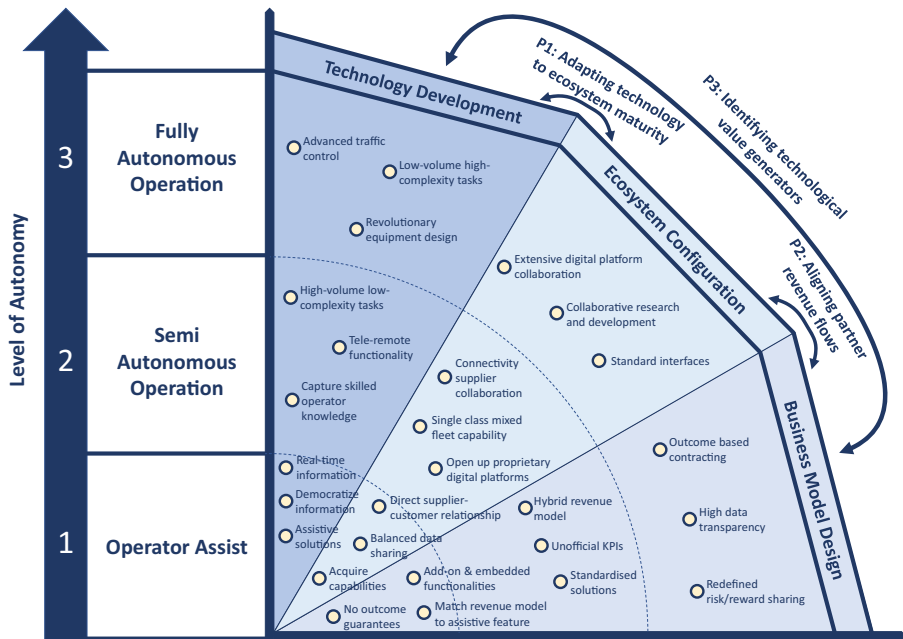


Fig. 2 A framework for commercialization of autonomous solutions

maturity of the delivery organization serving the customer (e.g. independent dealers). Equipment manufacturers may also consider new collaborations – for example, with SMEs and even competitors – recognizing that more advanced solutions will require the combined technologies and capabilities of various industrial actors.

Second, *aligning partner revenue flows* helps to ensure win–win scenarios for the different ecosystem actors involved in the autonomous solution. This is achieved by ensuring that the business model incentivizes the desired behaviors. Highlighting the need for alignment, respondents furnished instances where the shift to autonomous solutions could well conflict with the incentives of local delivery organizations that are structured for more traditional equipment sales. Therefore, there is a need to consider how incentives are structured and partner revenue flows are aligned, given that autonomous solutions will require risks and responsibility to be shared, and outcomes co-owned.

Finally, *identifying technological value generators* means that an important part of autonomous solution commercialization lies in identifying the use cases where increased automation can solve customer pain points. For example, a mine operator described the challenges of trying to improve the efficiency of energy-intensive production systems. The solution was to incorporate an autonomous operational capability, which resulted in a 21 percent cost saving. Indeed, successful commercialization of autonomous solutions requires identification of the ‘sweet spot’ areas where the autonomous solution creates most value. High-volume and low-complexity tasks such as the haulage of mining materials between two site locations are typically the first to become automated. When autonomous solutions develop the capability to handle

mission deviations and learning, it then becomes possible to automate higher-complexity tasks.

In sum, consideration of these overarching principles can assist equipment manufacturers in the successful commercialization of autonomous solutions by aligning technology development, ecosystem configuration, and business model design.

Discussion

Theoretical contributions

This study contributes to the existing digital servitization literature by analyzing and conceptualizing autonomous solutions, the most advanced form of digital servitization capability (Kohtamäki et al. 2019; Porter and Heppelmann 2014). By showing the key activities that industrial equipment manufacturers should undertake in the development and commercialization of autonomous solutions, the study makes three specific contributions.

Firstly, the study contributes through the development of a maturity framework for autonomous solutions that captures the dimensions of *technology development*, *ecosystem configuration*, and *business model design* across three levels of maturity. Maturity models have been developed for a range of different applications, but we have found none for autonomous solutions. Extant literature has restricted its focus to making abstract classifications of autonomous solutions existing at the higher end of a linear digitalization capability scale (e.g. Kohtamäki et al. 2019; Parida et al. 2019; Porter and Heppelmann 2014) and going some way toward recognizing that autonomy requires a more graduated perspective. The development of autonomous solutions has been characterized by an incremental development curve, where add-on technologies enhance the level of automation until full autonomy is reached (Darling 2011). We fill this gap by defining three levels of maturity for autonomous solutions (level 1: operator assistance, level 2: semi-autonomous operation, level 3: fully autonomous operation). We argue that the framework structured on these three levels of maturity provides a more comprehensive perspective on autonomous solution development than is currently communicated in the literature.

Secondly, the study contributes by emphasizing the interplay between the three dimensions of *technology development*, *ecosystem configuration*, and *business model design*. Along with technology development, companies need to develop a specific focus on ecosystem configuration (Sklyar et al. 2019a, b) and business model design (Parida et al. 2014; Reim et al. 2015). Prior studies have highlighted the expected transition to performance or outcome-based business models as a direct consequence of higher levels of autonomy (e.g. Lerch and Gotsch 2014, 2015; Parida et al. 2019). Our findings support this work, but we have identified hybrid revenue models as an additional intermediary step that enables this transition. In relation to ecosystem configuration, previous work has highlighted the need for greater collaboration in progressing to more technologically advanced solutions (e.g. Kohtamäki et al. 2019; Leminen and Wendelin 2018). Our findings support this need. However, we establish a more direct connection to autonomy by highlighting aspects such as data sharing and digital platforms that must be considered when configuring the ecosystem. In sum, we

support the perspective where successful technological development goes “hand-in-hand with adopting a servitization strategy” (Parida et al. 2015) that recognizes the importance of alignment with business model design and ecosystem configuration. Accordingly, as firms work towards higher levels of autonomous solution maturity, they need to move forward with their processes, capabilities, and offerings to create, deliver, and capture increased service value (Sjödin et al. 2020a, b).

Thirdly, whilst prior studies have discussed the possibility of developing and commercializing autonomous solutions, we provide empirical insights related to this context. Our investigation of autonomous solutions has earmarked a key challenge stemming from the lack of empirical cases that showcase a higher degree of digitalization capability in which commercial application is demonstrated. The empirical findings reveal a much more complex view of autonomous solutions than generically defined conceptualizations.

Managerial implications

Besides its theoretical implications, this study holds several implications for managers involved in industrial automation efforts and the development of autonomous solutions.

First, the maturity framework can serve as a readily applicable tool for industrial equipment manufacturers seeking to offer autonomous solutions to their industrial customers. The framework can be used as a roadmap for advancing the maturity level of the autonomous solutions offered, as it endorses activities that can be undertaken in pursuit of this endeavor. For example, the framework recommends manufacturer engagement in collaborative research and development activities to achieve the fully autonomous operation – working with a broad set of actors to integrate their capabilities into a joint solution. However, a direct supplier-customer relationship is likely sufficient for operator-assist functionality.

Second, by highlighting the interplay between technical-system evolution, ecosystem configuration, and business model design, the framework supports managers in taking a holistic perspective when making decisions concerning the development of autonomous solutions. Managers should consider all three attributes because focusing on one to the neglect of the others might not lead to the intended outcome. For example, to enable the advanced traffic control technology that fully autonomous solutions require, the manufacturer should configure ecosystem activities to include extensive digital platform collaboration, connecting assets from different industrial actors. This must be supported by a business model design that reflects the redefined risk/reward sharing arrangements, complemented by high data transparency for auditability and trust.

Third, although the framework focuses on the equipment manufacturer’s perspective, it can still help managers of the customer companies to procure autonomous solutions. For example, the framework can assist with the design of a template for evaluating and negotiating autonomous solutions because it highlights the key issues to consider, such as the most suitable business model design for the autonomous solution in question. This invariably leads to better informed negotiations for both parties. For example, guided by the framework, procurement managers seeking to acquire fully autonomous solutions will recognize the need for outcome-based contracting. This would promote a new type of interaction with suppliers, advancing from a transactional to a relational engagement built on mutual trust.

Limitations and further research

The present study's findings are built on case studies of four industrial equipment manufacturers in Sweden that are developing and offering autonomous solutions to their industrial customers. Although the empirical basis for our findings is fairly broad, we acknowledge that future research on autonomous solutions may be contingent on industry- or country-level differences, for instance. Disparities in culture and regulations between countries may play a role in ecosystem configuration and business model design for autonomous solutions. Consequently, we suggest further research on this aspect exploring the significance of such factors. In addition, we recommend further research to validate the maturity framework we have developed and to add weight to our conclusions. For example, studying the correlation between the maturity level of the autonomous solution and the business model design in other contexts could provide additional insights that enable a more generalizable framework to be produced.

Furthermore, our study lays the foundation for further research that seeks to develop a process understanding of business model innovation, capturing the phases and activities that industrial equipment manufacturers undertake when transitioning to increasingly advanced autonomous solutions. Similarly, the activities required to configure and transform the ecosystem can be further researched, investigating how to organize for internal and external knowledge and capability acquisition through, for example, collaboration with SMEs and even competitors. This will open up interesting issues for research such as how ecosystem actors can best achieve a balance between competition and cooperation.

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Conflicts of interest We confirm that there are no conflicts of interest.

Code availability Not Applicable.

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