Capabilities for the internet of things enabled product-service system business models

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ABSTRACT

The Internet of things (IoT) transforms how businesses operate, create, and deliver products and services. Despite increasing interest in IoT business models, knowledge of the capabilities needed to implement them remains vague. The objective of this paper is to investigate patterns found in 21 empirical tested cases covering several industries. This paper identifies the most common capabilities (connectivity, data management and storage, monitoring, data analytics, control, operations management, maintenance, communication, applications, and security) in an IoT-Product Service System (PSS). Industry practitioners can use this information to visualize linkages between their intended business model and capabilities when developing IoT-PSSs.

Keywords: IoT, product-service system, business model, capabilities

1. Introduction

The Internet of things (IoT) is a novel paradigm of Internet-based services supported by sensing technologies and smart components that enable firms to develop new types of business models - the design or architecture of a firm's mechanisms to create, deliver and capture value (Teece, 2010) - based on a marketable set of products and services capable of jointly fulfilling a user need by selling functionally rather than product ownership, defined as a Product-Service System (PSS) (Goedkoop *et al.*, 1999). We describe these as "IoT-PSS," which utilize smart sensors and devices, cloud computing, and next-generation telecommunication networks to monitor, control, and optimize business activities, capture, and deliver value for stakeholders (Osako *et al.*, 2019;

Tukker, 2004).

In this context, IoT-PSS's focus on selling integrated bundles of tangible products, intangible services, and digital architectures that fulfil individual customer demands digitally. This requires businesses to transform long-standing business models (Teece, 2010) and develop necessary capabilities. It is essential to identify the fundamental change in capabilities in industries not fully leveraging IoT (Hasselblatt *et al.*, 2018). Recent research identifies capabilities, including digitalization, service creation or maintenance (Ingemarsdotter, Jamsin, and Balkenende, 2020; Kohtamäki *et al.*, 2020; Nittala *et al.*, 2021) but the overall view is still fragmented. It also identifies IoT-PSS cases but has not shown the most typical combinations of capabilities and business models. Digital transformation literature discusses capabilities but does not put them into an IoT context (Warner & Wäger, 2019). Knowledge of capabilities in the digital era (Nasiri *et al.*, 2020), specifically, those needed to develop IoT-PSS business models, research in this area remains vague and in-depth qualitative studies could help develop a more detailed understanding (Kohtamäki et al., 2020; Hasselblatt et al., 2018). Through a qualitative case study, we answer the research question: What operational capabilities are necessary to implement business models through IoT-PSSs?

To address this research question, we conduct a multiple case study examination of 21 IoT-PSS testbeds to identify operational capabilities. These testbeds allow companies to trial run IoT-PSS solutions in mutually beneficial, high-value exchanges between business units and customers. Our contribution shows the most prominent operational capabilities from testbeds, which helps industry practitioners visualize linkages between capabilities and their IoT-PSS.

2. Theoretical background

A business model is a logic through which firms design the architecture and mechanisms they use to create, deliver, and capture value for stakeholders through their activities and offerings (Fjeldstad and Snow, 2018; Teece, 2010). The business model also describes a system of independent activities, which involves engagement of human, physical and capital resources performed by a focal firm and its partners, plus mechanisms linking these activities together to fulfil an objective (Zott and Amit, 2010). The strength of a firm's capabilities helps shape its aptitude at business model design. Capabilities are complex bundles of skills and knowledge embedded in organizational processes a firm performs well relative to rivals, and enables them to achieve their objectives through effective transformation of resources into valuable outputs (products, services, processes, and systems) (Saunila, 2020; Tho, 2018). As such the crafting, refinement, implementation, and transformation of business models are outputs of capabilities that allow firms to integrate, build, and reconfigure their internal competences to address, or in some cases bring changes in business environments (Teece, 2007, 2018). Firms transform their business models to combine technological innovation and knowhow with tangible and intangible assets to create and capture new sources of value (Teece, 2018; Nasiri *et al.*, 2020). We contend that the concept of IoT-PSS business models should be investigated from a capability's perspective, which help firms to develop appropriate capabilities and novel business models.

2.1Internet of Things product-service systems (IoT-PSS)

IoT is a relatively new and potentially disruptive computer paradigm in which machines, spaces, and humans interconnect with each other through the widespread deployment of spatially distributed devices. These devices have embedded identification, sensing and actuation capabilities equipped with wireless sensor networks and radio frequency identification (Miorandi et al., 2012) that facilitate creation of data-based product-service applications, which support day-to-day living, including smart-environments and human activity monitoring. From a business perspective, IoT is driven by two underlying trends: i) change of focus from viewing IoT primarily as a technology platform to viewing it as a system in which multiple stakeholders come together to deliver innovations; and ii) a shift from focusing on business models of a firm to designing new collaborative business models focusing increasingly on PSS (Westerlund *et al.*, 2014), and fact-based decision-making based on real-time information (Zancul *et al.*, 2016).

In this context, a PSS is a system of products and services capable of jointly fulfilling a user's needs and enable firms to be competitive (Mont, 2002; Goedkoop et al., 1999). They also signify a shift from tangibility to intangibility (Tukker, 2004), and the presence of networks (Mont, 2002). PSSs are complex innovations developed through interactions and collaboration between a diverse range of actors (Nair and Blomquist, 2021), who pool/integrate their internal and external capabilities to co-create value, accelerate internal innovation, and expand target markets (Grönroos and Voima, 2013). PSSs enhanced with IoT capabilities, allow firms to create virtual representations and access uniquely identifiable and connected objects - also referred to as "smart things” (Langley *et al.*, 2020). Permitting remote location, sensing and analysis, control and/or maintenance of smart things with real-time data/information flows between them (Langley *et al.*, 2020; Ng and Wakenshaw, 2017), enhancing a firm's ability to operate efficiently and effectively, particularly if smart things allow them to concentrate on their core activities (Langley *et al.*, 2020).

2.2. Business Models that utilize IoT-PSS and associated firm capabilities

IoT and PSS studies highlight the importance of business models in their successful development and implementation (Mont, Dalhammar, and Jacobsson, 2006). IoT-PSS facilitates business models that exploit its omnipresent nature to collect and analyze data on product-services, and capture value (Atzori, Iera, and Morabito, 2010; Lu, Papagiannidis, and Alamanos, 2018). The embodiment of IoT-PSS enables firms to increasingly work with their partners when altering elements of their business models, pool knowledge resources (Boudreau, Lacetera, and Lakhani, 2011), and develop products and services dependent on larger platforms and ecosystems compromised of firms, individuals, and other relevant actors (Hagiu and Wright, 2015). By surveying capabilities from previous literature on business models and IoT-PSSs, we synthesize five main types of business model that utilize IoT-PSS and expected main firm capability requirements (Table 1).

Table 1. Business models that utilize IoT-PSS and main firm capability requirements

Business Model type	***Description***	***Technological architecture governance of focal firm***	***Expected main capabilities***	***Example cases from literature***
Platforms	Multisided platform: Complementors provide assets Asset-sharing platform: Platform owner owns assets	Platform	Integrative capabilities	Map bar (Rong *et al.*, 2015) Car rentals (Rong *et al.*, 2015) Physical Internet (Qiu et al., 2015)
Tracking supply chains	Improvements to supply chain via IoT-based applications	RFID technology or similar sensors and data management facilities	Operational capabilities; Analytical capabilities	Hamburg seaport (Ferretti and Schiavone, 2016) Pharmaceutical supply chain (Papert, Rimpler, and Pflaum, 2016)

Asset management	Maintain and control assets or environments via IoT-based applications	Sensors	Service-related data processing and interpretation capabilities; system integration capabilities	Land resource supervision (Fang *et al.*, 2017) Maintenance (Zancul *et al.*, 2016)
Adjusting manufacturing processes	Send customer information about necessary actions to adjust processes based on real-time data	Sensors and data management facilities; analytical software	Service-related data processing and interpretation capabilities	Car operating platform (Rong *et al.*, 2015) Predictive machine setup (Zancul *et al.*, 2016)
System and communication security	Provide security as part of the PSS	Multiple technical layers	IT capabilities	Security in pharmaceutical supply chain (Papert *et al.*, 2016)

(1) Platforms - multisided platforms enable direct interactions and value exchange between two or more distinct sides (end-users and complementary businesses) affiliated to the platform (Hagiu and Wright, 2015; (Eloranta and Turunen, 2016). Typically, a focal firm needs integrative capabilities that ensure orchestration of complementary asset providers and input suppliers (Helfat and Raubitschek, 2018). Some platforms differ from multisided platforms as the platform owner also owns shared assets (i.e., goods and services) and controls the main terms of interactions between parties (Qiu et al., 2015).

(2) Tracking supply chains – service providers collect and analyze data using tracking systems and sensors embedded in objects to provide accurate identification, routing, and conditioning services. This enables improvements in supply chain efficiency and reduces management costs through advancements in product and process traceability, visibility, and information accuracy (Sarac, Absi, and Dauzre-Prs, 2010). Analytical capabilities enable data interpretation and drawing conclusions which bring improvements in operations, e.g., advanced visualization of production processes and advanced traceability of inventory or logistics (Fatorachian and Kazemi, 2021). Process integration capabilities refer to the magnitude of intra- and inter-business process integration, information sharing, process automation, synchronization and coordination that ensure interoperability characterize this business model type (Han, Wang, and Naim, 2017).

(3) Asset management - service providers monitor physical assets or an environment using tracking systems and sensors that collect, analysis and interpret data and allow service providers or third parties to take necessary actions to maintain assets (Ingemarsdotter *et al.*, 2020). Capabilities for asset management include system integration, and a firm's ability to design, manufacture, sell and

deliver products and service components (internally or externally) and integrate them into customer-specific solutions (Windahl and Lakemond, 2010). This includes pure technological capabilities a firm uses to translate a customers' business goals into technical specifications efficiently and cost-effectively.

(4) Adjusting manufacturing processes - a provider applies iterative data exchange loops to develop a predictive and intelligent analysis of a customer's manufacturing processes based on real-time data extracted from sensors located on a site to inform customers of necessary actions to improve them. IoT allows internal manufacturing systems to vertically network with business processes and horizontal connections to disperse external value networks in real-time (Ingemarsdotter *et al.*, 2020). This enables and requires end-to-end engineering and integration of processes across entire value chains.

(5) System and communication security - service providers use their technological ability to secure dataflow and prevent undesirable data modifications and leakages - a constant issue in IoT-PSS applications and associated physical devices due to their omnipresence (Li, Tryfonas & Li, 2016; Qiu et al., 2015). The challenge is to sustain utility while minimizing complexity created by privacy and security requirements (Qiu *et al.*, 2015).

3. Methodology

3.1 Data collection

To develop an accurate description of IoT-PSS business models and necessary capabilities, we adopted a multiple case study approach. Case studies apply multiple levels of analysis and replication logic when same findings are in multiple cases (Eisenhardt, 1989). The case study data is from the Industrial Internet Consortium testbed database (Table 2). We selected these 21 IoT testbed cases due to their concentration on IoT and detailed focus on how value is created for customers and with which capabilities. The IoT consortium is an independent actor that coordinates IoT-related business and technology development work conducted in joint projects between leading firms in the field. According to the Industrial Internet Consortium, '[a] testbed is a controlled experimentation platform, conforming to an Industrial Internet Consortium reference architecture, where solutions can be deployed and tested in an environment resembling real-world conditions.' In this sense, a testbed is a neutral experimentation platform for conducting rigorous, transparent, replicable testing of new concepts, computational tools, and technologies in a collaborative ecosystem of leading experts (Industrial Internet Consortium, 2021).

Table 2. Sample testbed cases overview

Testbed	Testbed Description	Number of Companies	Industrial Sector	Location
1	IoT-enabled smart assets: cloud-based services and applications.	4	Utilities	Asia
2	IoT-enabled healthcare: remote home monitoring and continuous healthcare.	4	Healthcare	USA
3	IoT-enabled baggage systems: smart asset-tracking.	4	Transport	USA
4	IoT-enabled factory: smart and automated operating systems.	3	Manufacturing	Asia
5	Security platform: continuous monitoring of operational processes and identification of irregular incidents.	13	Security	Multinational
6	IoT-enabled legacy systems: integration of smart systems and existing ICT systems in manufacturing scenarios.	4	Manufacturing	Europe
7	IoT-enabled factory: visibility, traceability, and optimization of factory floor processes.	2	Manufacturing	Asia/USA
8	IoT-enabled predictive maintenance: online measurements and automated analysis.	3	Predictive Maintenance	USA
9	IoT-enabled manufacturing processes and procedures: smart analytics and data in design, manufacturing, service, and supply-chain setup stages.	2	Digital Integration	USA
10	IoT-enabled asset management: real-time asset information and operational decision-making.	8	Digital Integration	Multinational
11	IoT-enabled smart grids: more accurate and reliable power generation.	3	Energy	USA
12	IoT-enabled communication networks: support of real-time control and synchronization of high-performance machines.	11	Manufacturing	Multinational
13	IoT-enabled energy management systems: monitor, visualize, analyze, and optimize energy consumption within different settings.	3	Digital Integration	Multinational
14	IoT-enabled water infrastructure management: reduction of water loss through early and pre-emptive detection of leaks and precision irrigation of watered areas	4	Digital Integration	Multinational
15	IoT-enabled factory: creation and validation of new business models.	2	Manufacturing	Asia/Europe
16	IoT-enabled end-to-end traffic infrastructure ecosystem: pre-empt and prevent road congestion, automatically identify unusual events on the road and facilitate cooperative point-to-point travel.	3	Transport	Multinational
17	Introduction of high-speed fiber optic lines to support industrial Internet initiatives: machine-to-machine communications and data transfer across connected control systems, big infrastructure products and manufacturing plants.	4	Digital Integration	Multinational
18	Software-defined infrastructures to drive growth of industrial Internet products and services, particularly through mobile networks.	2	Digital Integration	Europe/USA
19	IoT-enabled agriculture: improved crop management and yield, reduction of environmental impact.	2	Agriculture	USA
20	Industrial IoT applications: coordinated, real-time analytics test environment for other testbeds.	2	Digital Integration	USA

21	IoT-enabled factory floor: efficient tracking and tracing of usage of tools.	4	Manufacturing & Supply Chain	Multinational

Our sample cases varied in terms of the firm's capability requirements and business area, covering a wide range of processes and IoT technologies (energy, health care, manufacturing, smart cities, and transportation). Firms involved in the case study testbeds include large, multinational organizations, and in some cases local authorities and academic institutions.

3.2 Analysis of cases

Case documentation was available as text documents which we coded and analyzed qualitatively using NVivo software. Our general analytic strategy was to start a data-driven, inductive coding of capabilities. First, we employed case analysis and open coding to identify capabilities from the raw data if it presented skills or knowledge necessary for IoT-PSS outcomes. This enabled us to identify common themes amongst testbeds, which were aggregated into groups based on their similarities, which were labelled to describe groupings (first-order codes). Figure 1 shows our data structure for capabilities (Gioia, Corley, and Hamilton, 2013). We coded First-order codes are called lower-order capabilities, and second-order codes are called higher-order capabilities. Second-order codes were made by the researchers by reflecting first-order codes. Data analysis revealed 10 higher-order capabilities. Finally, two researchers reflected on and compared testbed cases (Table 1) against cases, business models and descriptions found in literature. If similar, we added the testbed under that business model type (Table 3 in Findings) allowing us to connect cases and capabilities to business model types.

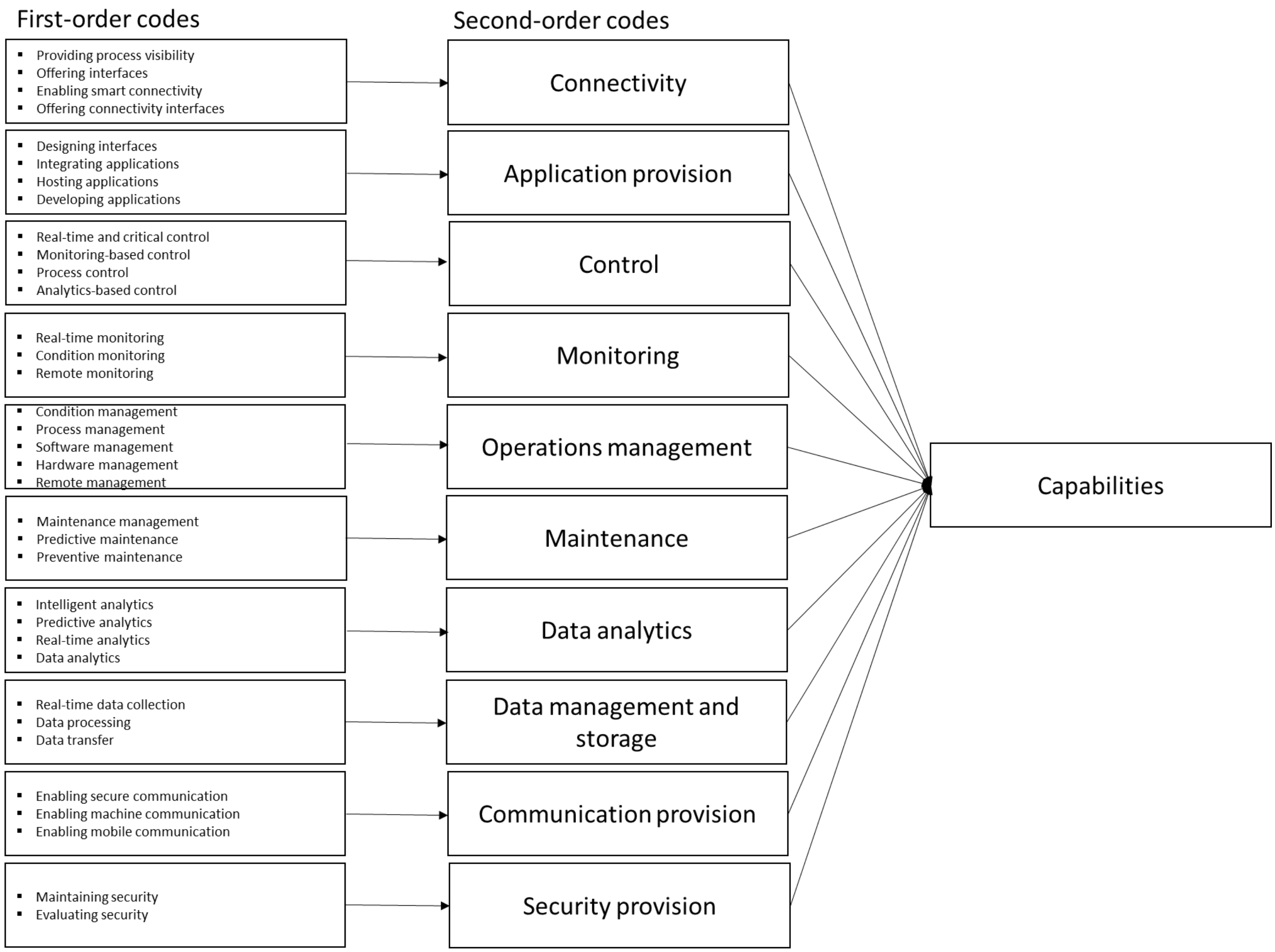

Figure 1. Data structure of capabilities.

4. Findings

4.1 Main observations of cases

Qualitative analysis of the 21 cases identified 10 higher-order capabilities (Table 3): connectivity, application provision, control, monitoring, operations management, maintenance, data analytics, data management and storage, communication provision and security provision (described in chapter 4.2). Table 3 shows cases similar business model types found from literature (platforms, tracking supply chains, asset management, adjusting manufacturing process and system, and communication security).

Platforms were found from cases emphasizing connectivity, including Case 2 which operates healthcare data management and analytics platforms. Tracking supply chain business models like Case 3, track moving objects like luggage, providing services connecting otherwise fragmented applications and let customers view the status of their luggage. Asset management business models highlight monitoring, maintenance, and context-specific data analytics capabilities. For instance, Case 1 increases water safety by monitoring its quality and provides analytics to detect sources of degradation. Adjusting manufacturing process business models require data management and storage, communication provision, connectivity, data analytics and monitoring capabilities. Case 11, for example, is about integrating solar and wind power into the grid efficiently and reliably with flexibility of real-time analytics. Finally, system and communication security business models like Case 5 based on evaluating and detecting security vulnerabilities.

Table 3. Capabilities and cases

	Case number	**Connectivity**	**Application provision**	**Control**	**Monitoring**	**Operations management**	**Maintenance**	**Data analytics**	**Data management and storage**	**Communication provision**	**Security provision**
Platforms	2	x			x	x			x		
	4	x	x			x	x	x			x
	18	x								x	x
	20			x				x			
Tracking supply chains	3	x	x			x		x	x		
Asset management	1				x		x	x			
	8				x		x	x	x		
	9						x	x	x		
	10				x	x	x	x	x		
	12	x	x	x			x				
	14				x	x					

	16	x			x			x		x	
	21		x			x	x				
Adjusting manufacturing process	17	x							x	x	
	6	x	x						x	x	
	7	x		x		x		x	x		
	11		x	x				x		x	x
	13		x		x	x					
	15	x	x		x					x	x
	19		x		x			x	x		
System and communication security	5	x	x					x		x	x

4.2 Capabilities of cases

In the following paragraphs we explain what main- and lower-order capabilities are found in the cases and in which context (see Appendix for case-by-case summary). *Connectivity* enables data access and interactions through gateways, devices or other access points and allows it to be combined with data gathered elsewhere.

Lower-order capabilities of connectivity are process visibility, offering interfaces, and enabling smart and secure connectivity (Figure 2). Process visibility refers to visibility of assets during a process. Smart baggage tracking in Case 3 is an example of a process requiring visibility. Capability to offer interfaces is especially important in cases where monitoring must be accurate, reliable, and continuous like in monitoring irregular security incidents in continuous operations as in Case 5. Connectivity through interfaces beyond operating systems' boundaries is important when the objective is to control and manipulate physical devices in IT systems within manufacturing in Case 6. Capabilities of designing and enabling smart, and secure connectivity are necessary when varying stakeholders are monitoring movement of assets like in baggage tracking in Case 3, automated operating systems in Case 4, traffic infrastructure systems in Case 16 and information integration in manufacturing plants in Case 17.

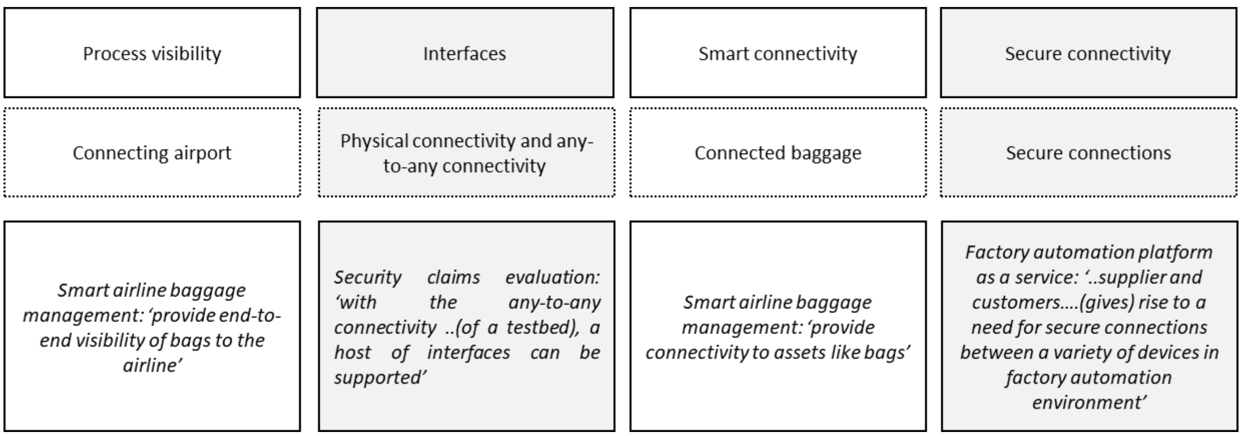

Figure 2. Lower-order capabilities of connectivity.

Application provision refers to development of a program(s). This involves designing interfaces and developing, integrating, and hosting applications (Figure 3). Capability to design interfaces is critical in building systems for monitoring as there must be smart algorithms that automatically capture abnormalities and thus help monitor tasks e.g., security monitoring in Case 5. Interface design capability is also critical when accuracy and speed is required as in energy smart grids in Case 11. Development of applications may require a firm to bring fragmented applications together, resolving questions of interface design between these applications like in integrating separate systems in Case 6, synchronizing machines in Case 12, and building a digitalized factory in Case 15. Application integration and hosting capabilities appear to be crucial in energy management systems, e.g., Cases 11 and 13, as the energy market is global, regulated differently among countries and energy sources, and is in a transition phase due to emerging new energy sources. Application integration capability is needed when data volumes from different sensors are high like in Case 19. Application development capability is important in tracking and operating related tasks where the location or condition of assets or products must be known all the time, and information must be in easily usable forms as edge device management of baggage trucks and scanners in Case 3, remote operations in Case 4 and locating power tools in factories in Case 21.

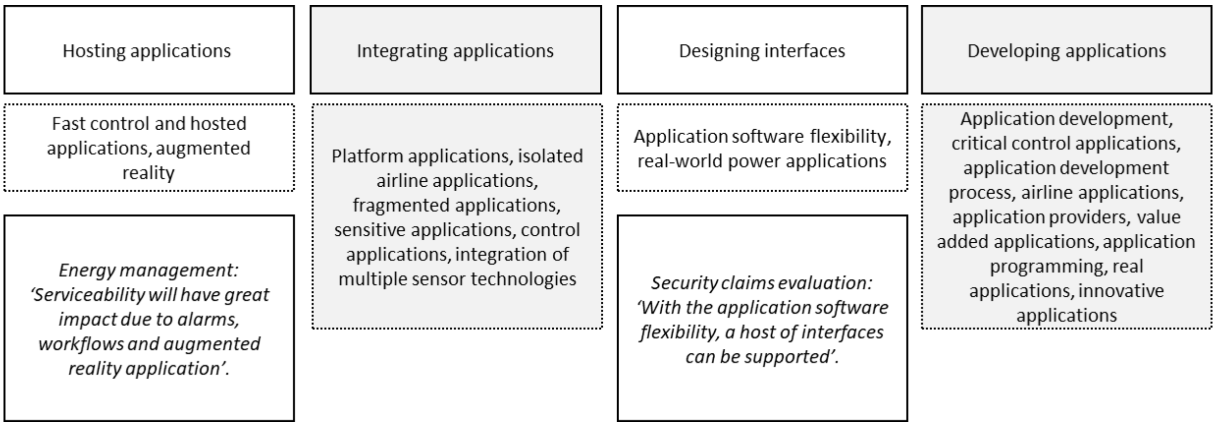

Figure 3. Lower-order capabilities of providing applications.

Control enables and ensures more accurate and reliable processes, for instance in the field of power generation, manufacturing, or repair processes. This requires lower-order capabilities include real-time -, critical -, monitoring -, process- and analytics-based control (Figure 4). Real-time and critical control describes control over industrial devices with relation to surroundings, which is a base of control service solutions e.g., in Case 12. Monitoring and process-based control requires an understanding of priorities and bottlenecks in processes, which is a larger knowledge base than management of the technical control of devices. These capabilities are required in providing combined information in a useful format from multiple data sources, for example, process, machine and schedule status in Case 7, synchronization of high-performance machines in Case 12 and coordinated real-time analytics in Case 20. A firm needs analytics-based control capability to provide control applying these analytical solutions, for example, to operate reliable power generation as in Case 11.

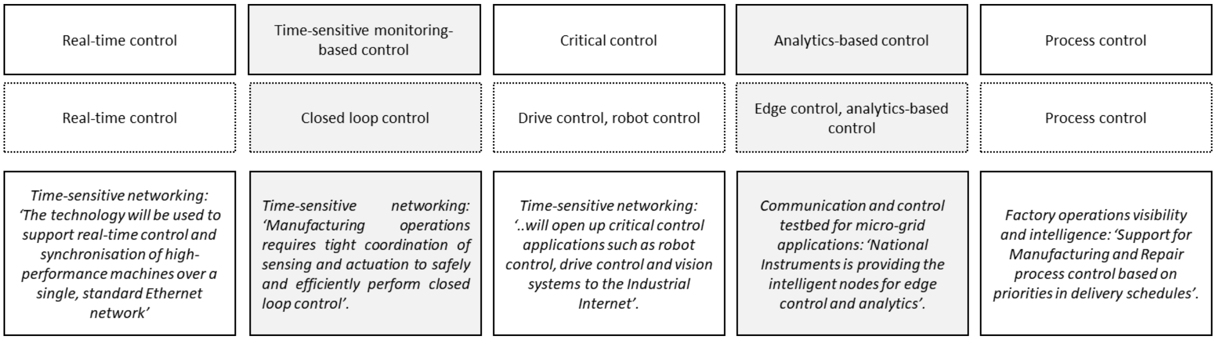

Figure 4. Lower-order capabilities of control.

Monitoring refers to tracking data flow and requires lower-order capabilities of real-time, condition and remote monitoring (Figure 5). Realtime monitoring capability is needed especially in cloud-based water supply management in Case 1. Condition and remote monitoring capabilities include expertise on the quality of an object. This may be an outcome from data analysis of inputs from multiple real-time sensors. Service providers transfer data away from monitoring locations, and remote monitoring enables efficient data analysis with economics of scale and scope. These are especially relevant in continuous healthcare related monitoring in Case 2, optimization related tasks like energy consumption optimization in Case 13, and water loss management in Case 14 requires condition monitoring capabilities. Reducing downtime with maintenance planning in Cases 8 and 10 are also examples of monitoring capabilities.

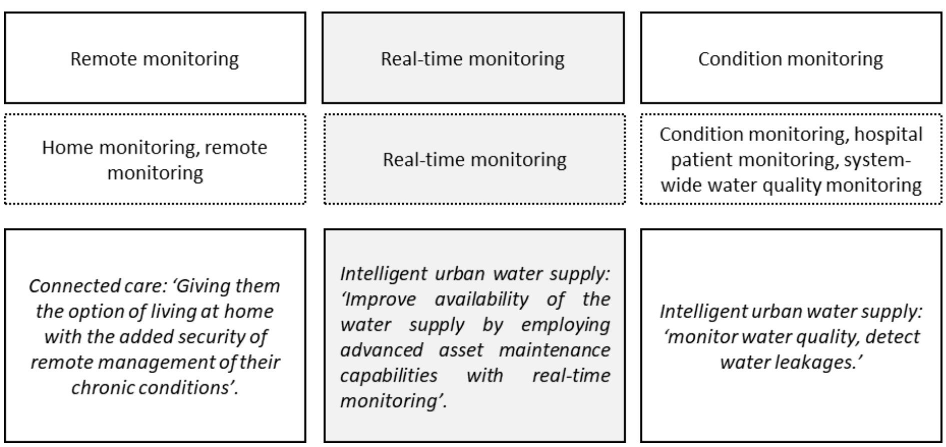

Figure 5. Lower-order capabilities of monitoring.

Operations management refers to capability to do activities with tools that facilitate operations and decision-making, like augmented reality tools and workflow platforms. Lower-order capabilities for operations management are condition, process, software, hardware, and remote management (Figure 6). Condition and process management refers to knowledge about preferred actions when there are signals from monitored objects that require corresponding actions from a service provider. This is required for example in home monitoring in Case 2, baggage management in Case 3 and operating automated factory in Cases 4 and 21. Full responsibility of a certain process demands understanding the order of necessary actions. Software and device management relate to situations where hardware management and corresponding software management must align, and their continuous operation is critical. This is the case when managing patients' health in Case 2. Remote management is needed in all cases when operating conditions from a distance including energy management systems in Case 13 and water infrastructure management in Case 14.

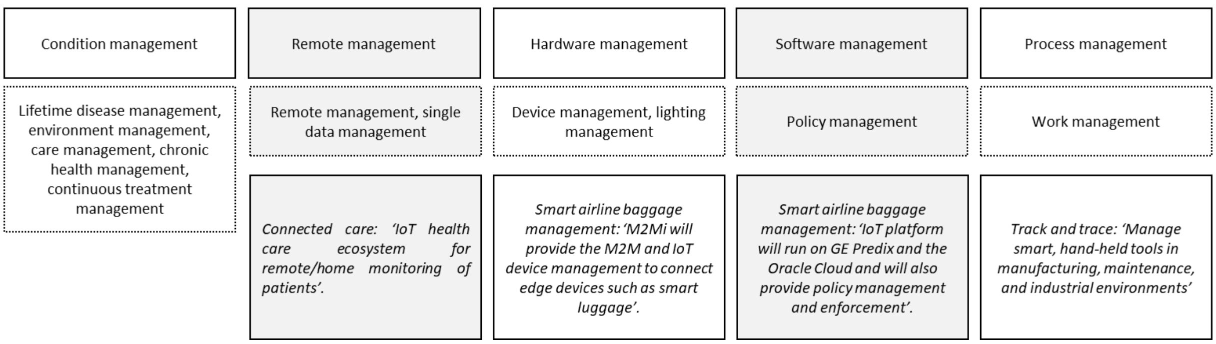

Figure 6. Lower-order capabilities of operations management.

Maintenance refers to maintaining or preserving some condition of an asset and relates to maintenance management, and predictive and preventive maintenance (Figure 7). Predictive maintenance enables service providers to fix equipment when it is most convenient and disengage itself from fixed maintenance schedules. This is needed in intelligent water supply network in Case 1, factory automation in Case 4 and maintaining high value assets in Cases 8 and 21. Preventive maintenance leads to fewer errors and improves reliability of processes. Preventive maintenance is needed, for example, to improve water supply reliability in Case 1, service teams keeping large industrial assets working in Case 9 and ensuring operation of time sensitive networks in Case 12. Management of maintenance is part of a more efficient service solution when IoT enables preventive and proactive maintenance actions. These capabilities are especially relevant in Case 10 which focuses on developing IoT enabled asset management. The cases underscore real-time data collection, data management and data analysis capabilities essential when a firm is providing maintenance service.

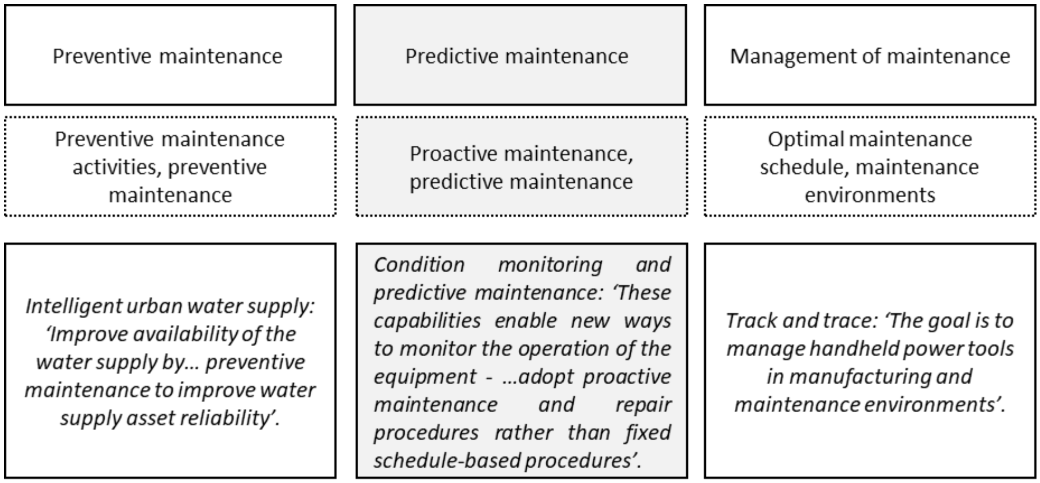

Figure 7. Lower-order capabilities of maintenance.

Data analytics means modelling and transforming data to find useful information for decision-making purposes and requires capabilities, including intelligence, predictive, and real-time analytics (Figure 8). Analytics highlight the need to make good decisions based on correct analytical conclusions. Intelligent and predictive analytics is related to the operation of information networks, e.g., to improve awareness, predictability, and connectivity in Cases 3, 9, 11, 16, 19 and 20 and optimizing water supply network in Case 1. Real-time analytics and intelligence are a core capability of IoT services, which firms must develop and may require a larger scale of computation and higher velocity to fulfil customer needs. For example, real-time analytics is necessary in ensuring reliable and accurate power generation in Case 11, providing large scale computation at the edge of network in Case 20, providing efficiency in Case 10 and providing information security in Case 5. In these cases, capability of data analytics coexists with predictive and preventive maintenance capabilities and analytics-based control.

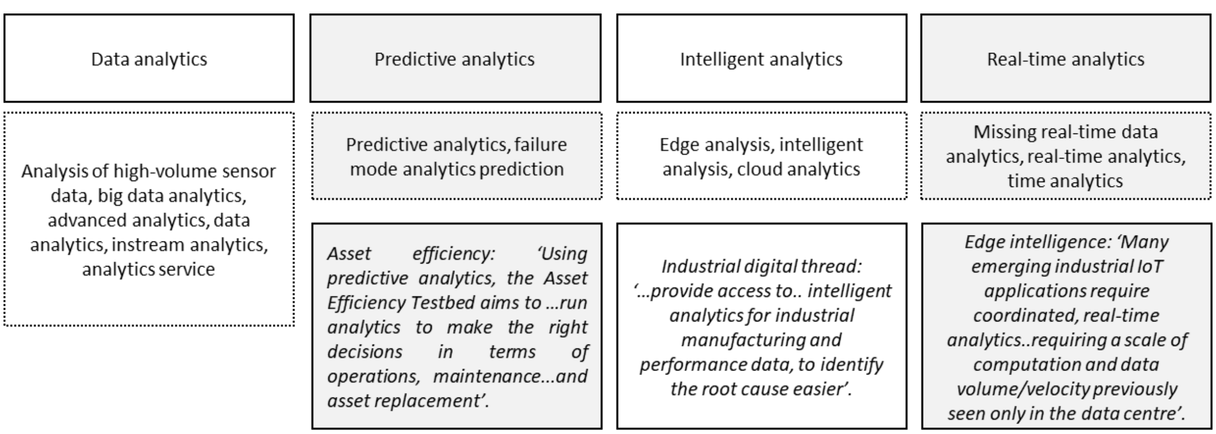

Figure 8. Lower-order capabilities of data analytics.

Data management and storage refers to data collection from various sources, and structuring and storing it in databases. Data management and storage requires capabilities of real-time data collection, data processing and transferring, integration and smart connectivity (Figure 9). A service provider in an IoT business needs to manage increasing amounts of data, combinations of data, and data storage and transfers. Real-time data collection and processing is related to developing a platform for efficient data management in Cases 2, 9 and 10. Data transfer capability is needed to operate seamless communication of e.g., between machines in Case 17. Integration is especially important when there are several data sources critical in decision making, as in-patient monitoring in Case 2 and improving efficiency in industrial processes in Case 8. S Structures like data aggregation policies make data management more efficient. This requires capabilities of smart connectivity like in Case 6.

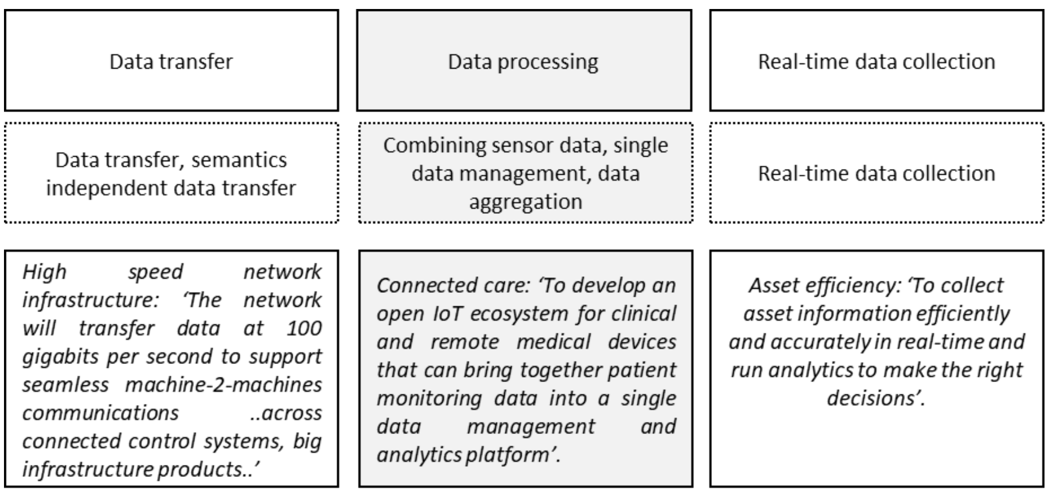

Figure 9. Lower-order capabilities of data management and storage.

Communication requires enabling secure machine and mobile communications (Figure 10). Case 11 highlights the scale of communication types, including machine-to-machine or machine-to-cloud, and a variety of communication types adds complexity from a service provider's standpoint. For instance, aggregation of communication from various sources to control centers requires expertise and secure communication. Mobility also creates specific requirements for connectivity, including dynamic configuration of mobile communication in Case 18 and intelligent traffic in Case 16. Another special requirement is high network speed like in Cases 15 and 17. Capability of data transfer and integration between machine-to-machine or machine-to-cloud in a secure way like in Case 5 is essential.

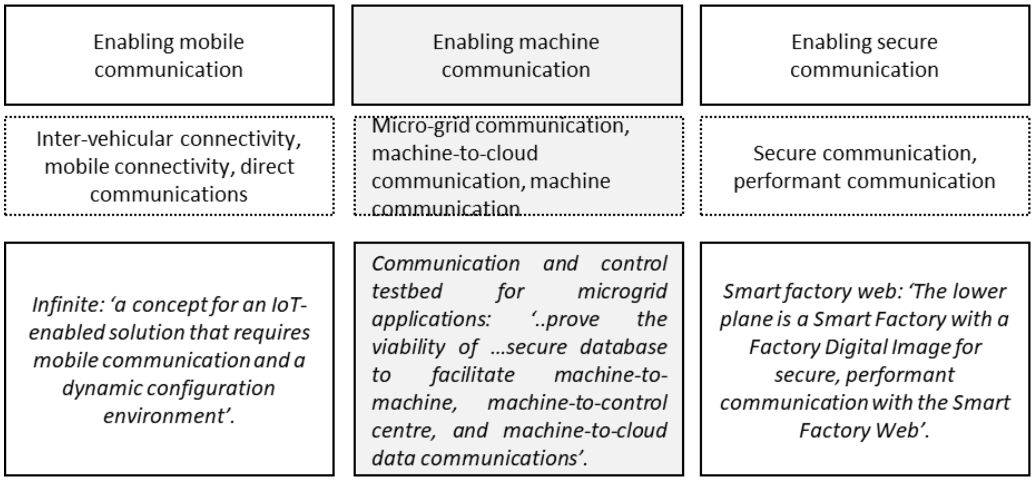

Figure 10. Lower-order capabilities of communication.

Security provision capability requires skills in maintaining and evaluating security (Figure 11). Capabilities to manage interfaces and secure connectivity are evaluated in Cases 5 and 18, which seek security vulnerabilities and maintain security levels. Security needs to be ensured at device and system levels prior larger scale deployment or renewal. For example, in Case 5, manufacturers were willing to test their own products before launching security claims evaluations. Security maintenance refers to continuous actions that ensure secure connections. These secure connections between devices of distinct stakeholders facilitate participation in automated environments like in Case 11.

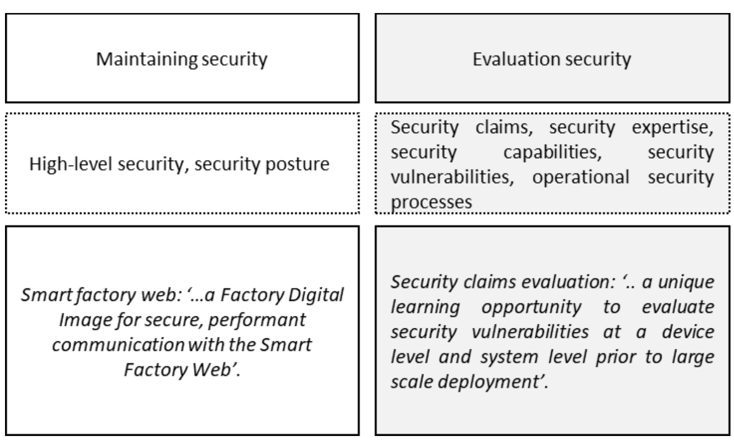

Figure 11. Lower-order capabilities of security provision.

5. Discussion and conclusions

5.1 Theoretical implications

The aim of this research was to clarify operational capabilities necessary for implementing IoT-PSS business models (Kohtamäki and Baines, 2019; Nasiri *et al.*, 2020). The analysis showed decomposing an IoT testbed environment into its required capabilities offers valuable insights into ways to handle the inherent complexity of business models described in earlier studies (Nair and Blomquist, 2021; Paiola and Gebauer, 2020). We contribute on IoT-PSS business model research by showing what kind of capabilities are necessary for IoT-PSS business models (Table 4). Lower-order capabilities are within higher-order capabilities when focusing on more detailed operational capabilities and this research shows this hierarchy in its findings. As implication to discussions on business model transformation (Holtström, 2021; Teece, 2018), we show examples of refined IoT-PSS business models (seizing) and guide alignment and investments in capabilities (transformation).

Table 4. Research contribution

Capability	Examples of IoT-PSS for this capability	Connection to previous literature of IoT related capabilities
Connectivity	Platforms, Adjusting manufacturing process, Tracking supply chains, Asset management	Connectivity (Brody and Pureswaran, 2015; Langley *et al.*, 2020)
Application provision	Tracking supply chains, Adjusting manufacturing process	Service development capabilities (Rönnberg Sjödin, Parida, and Kohtamäki, 2016)
Control	Adjusting manufacturing process	Control (Ingemarsdotter *et al.*, 2020; Meyer, Wortmann, and Szirbik, 2011)
Monitoring	Asset management, Adjusting manufacturing process	Monitoring (Ingemarsdotter *et al.*, 2020; Meyer *et al.*, 2011; Zancul *et al.*, 2016)

Operations management	Asset management, Adjusting manufacturing process	Business process redesign in logistics (Ferretti and Schiavone, 2016)
Maintenance	Asset management	Maintenance (Ingemarsdotter *et al.*, 2020)
Data analytics	All types	Data analytics (Fatorachian and Kazemi, 2021; Rönnberg Sjödin *et al.*, 2016)
Data management and storage	Platforms, Asset management, Adjusting manufacturing process, Tracking supply chains	Data management (Schoenherr and Speier-Pero, 2015)
Communication provision	Adjusting manufacturing process	Network management capabilities (Rönnberg Sjödin *et al.*, 2016) Collaborative capabilities (Langley *et al.*, 2020)
Security provision	System and communication security, Platforms, Adjusting manufacturing process	Security (Bujari *et al.*, 2018)

Specifically, our results found connectivity to be the most prominent capability, and it has been previously characterized as a main element for system-level smartness in business models utilizing IoT-PSS (Langley *et al.*, 2020). An IoT-PSS based business may focus on sensor networks, data, and device interfaces (connectivity and security provision) or predictive data analytics relating to production and business processes, as our findings suggest. Secondly, application provision and data analytics capabilities are present in many testbeds. Implying these capabilities are present in most service orientated IoT platforms. Previous research has emphasized the creation of services (Nittala *et al.*, 2021) but application provision capability at operational level has gained less attention.

Our results show maintenance capabilities include management related capabilities like optimal maintenance schedule and environment. Preventive and predictive maintenance capabilities are previously connected to IoT-PSS (Ingemarsdotter *et al.*, 2020) but we propose management of maintenance as a complementary capability. Our findings complement previous research (Daim, Basoglu, and Topacan, 2013; Zancul *et al.*, 2016) which reports that monitoring capabilities enable data flow for maintenance management is an established capability for IoT-PSS. Real-time monitoring of machine, process, and infrastructure performance in asset management may allow firms to implement data-driven services, predict changes in production systems and develop early warning systems for online risk management.

Potential monitoring capabilities are closely aligned to capabilities of control. Control capabilities refer to controlling and adjusting machines, or processes when monitored data and its analysis suggests doing so. It is also about controlling of amount of data sent by IoT sensors to networks, meaning a network of devices is monitored and controlled in terms of data transfer. Thus, control of data, control system for network, and monitoring and controlling of equipment and processes within the case context must be interlinked to accomplish IoT-PSS (Leminen *et al.*, 2018), which we synthesize as capability of control. This synthesis combines two viewpoints: IoT device related discussions on control of large amounts of data (Fang *et al.*, 2017) and control of processes or machine adjustments in IoT-PSS (Ingemarsdotter *et al.*, 2020; Meyer *et al.*, 2011).

Like Akhbar et al. (2016), we find data management and storage capability a key enabler in the testbeds and for IoT-PSS business models. For instance, tracking a supply chain, data management and storage increases visibility and allows exchange of more data, which can be used as a basis for supply chain coordination analysis. Operations management capability for IoT have been identified mostly in the supply chain field (Ferretti and Schiavone, 2016) but are relevant to many sectors, e.g., health care. Furthermore, to make accurate decisions, firms must identify the most relevant data for their purposes (Schoenherr & Speier-Pero, 2015). Capability of data management and storage is closely linked to analytics and communication capabilities. Data analytics have been previously described as descriptive if the end-result is data visualization, diagnostic if it ends in analysis, predictive if it anticipates anomalies in data, and prescriptive when optimizing processes through machine learning (Chettri and Bera, 2020). Our findings included equivalent capabilities. Communication between objects and its challenges, including congestion or costs in IoT context has been discussed extensively in engineering literature (Chettri and Bera, 2020), but has not been regarded previously as a capability that enables business opportunities for IoT-PSS. We also found communication is associated with a need for security provision capability. Security has been regarded as limiting IoT use if not well managed (Bujari *et al.*, 2018), our findings also emphasize the importance of security capabilities.

5.2 Practical implications

Reflecting on practical implications, this study provides firms guidance on the types of capabilities they are likely to require developing IoT-PSS business models in different operational contexts. This enables firms to realign their current structure and culture (Teece, 2018), and to assess what capabilities they currently possess or need to develop internally, and those that can be sourced through external networks.

5.3 Limitations and future research

This study contributes to the literature on IoT-enabled businesses by providing findings connecting IoT-PSS and capabilities required to resolve IoT-based business problems. The cases could not fully cover relevant aspects of the research subject including performance measurement of testbeds in monetary terms which is a limitation of this study. Future research could study IoT value creation and capture from the supply chain perspective to understand implications and capability requirements for each member of a PSS. Furthermore, from a technology business point of view, it would be fascinating to study competitive industry positioning in each part of the IoT architecture, to understand drivers behind the development and maintenance of business models utilizing IoT-PSS.

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