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CAPABILITIES FOR DATA ANALYTICS IN INDUSTRIAL INTERNET OF THINGS (IIOT)

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Research Paper

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Abstract

The use of Industrial Internet of Things (IIoT) technologies in various industrial sectors has resulted in the generation of large volumes of data that can be analyzed using analytics tools to improve firm performance. However, there is a gap in our understanding of the capabilities that companies need to create business value through data analytics in IIoT environments. Although previous research has extensively investigated general data analytics capabilities, the literature on these capabilities cannot be simply transferred to IIoT settings due to the unique characteristics of the IIoT. In this paper, we aim to contribute to our understanding of this phenomenon by identifying the capabilities required for IIoT data analytics. Firstly, we identify data analytics capabilities from existing literature. Next, we investigate the relevance of these capabilities in the context of IIoT, while also identifying novel capabilities that are specific to IIoT, by conducting 16 expert interviews within nine organizations. We identify a set of 24 capabilities for data analytics in IIoT, which we classify into an integrative framework. The proposed framework can assist industrial companies dealing with the complexities and uncertainties associated with IIoT data analytics initiatives.

Keywords: Industrial Internet of Things, IIoT capabilities, data analytics capabilities, Business value.

1 introduction

Today Internet of Things (IoT) technologies are drawing considerable attention from both academics and practitioners. Many organizations have been heavily investing in these technologies (Siow et al., 2018). McKinsey estimates that the number of businesses that use IoT technologies has increased from 13 percent in 2014 to about 25 percent in 2019 (Dahlqvist et al., 2019), and it predicts that IoT could enable $5.5 trillion to $12.6 trillion in value globally, by 2030 (Chui et al., 2021).

Industrial Internet of Things (IIoT) as a subset of IoT rapidly transforming the landscape of many industrial sectors, (e.g., smart manufacturing, logistics, retail, and utilities) by enabling smart automation, intelligent decision-making, and data-driven optimization (Boyes et al., 2018, Khan et al., 2020, Qi et al., 2023, Rehman et al., 2019). IIoT refers to the network of intelligent and highly connected industrial components that are deployed to achieve a high production rate with reduced operational costs through real-time monitoring, efficient management, and controlling of industrial processes, assets, and operational time (Khan et al., 2020).

In mission-critical industrial settings, IIoT requires higher levels of safety, security, and reliable communication without the disruption of real-time industrial operations (Qi et al., 2023). However, IIoT devices such as sensors, RFIDs, and actuators integrated with industrial equipment generate large volumes of diverse and heterogeneous data, which can be challenging to process due to restricted computing, networking, and storage resources (Boyes et al., 2018, Qi et al., 2023).

To derive business value and gain a competitive advantage, IIoT data must be collected, integrated, and analyzed in a scalable and cost-effective manner (Ahmed et al., 2017). To achieve this, data analytics tools play a vital role in transforming IIoT data into valuable business insights (Ahmed et al., 2017, Boyes et al., 2018, Côrte-Real et al., 2020, Rehman et al., 2019). However, incorporating data analytics in the context of IIoT presents various challenges, including interoperability and system integration difficulties, data offloading, missing data streams, network performance issues (such as congestion, delays, and bandwidth), system architecture, scalability, reliability, and security and privacy concerns (Khan et al., 2020, Qi et al., 2023). Nevertheless, in prior studies, most emphasis has been on the technical aspects of data analytics in IIoT environments (Ahmed et al., 2017, Côrte-Real et al., 2020, Marjani et al., 2017) while limited attention has been paid to understanding how to leverage them to generate business value.

Previous research on business value creation through data analytics has shown that while data analytics tools are necessary, they alone are not enough to produce business value (Gupta and George, 2016, Mikalef et al., 2018). One lens to study how firms leverage data analytics to realize performance gains is data analytics capabilities (Gupta and George, 2016, Mikalef et al., 2018, Wang et al., 2018). Drawing on the resource-based theory, data analytics capabilities refer to a company's ability to effectively collect, analyze, and interpret data by effectively managing and utilizing its data, technology, and talent to generate business insights (Akter et al., 2016, Gupta and George, 2016, Mikalef et al., 2018). While data analytics capabilities have been widely investigated in prior research, such as (Akter et al., 2016, Mikalef et al., 2019, Wang et al., 2018), due to idiosyncrasies of the IIoT data (like heterogeneity of data sources, real-time streaming data, data redundancy, limited communication range, restricted networking, and node failure (Boyes et al., 2018, Côrte-Real et al., 2020, Qi et al., 2023), the literature on data analytics capabilities cannot be simply transferred to the IIoT settings.

As with any new technology, such as that of IIoT, organizations need to develop a unique set of capabilities to effectively leverage their investments to generate business value (Mikalef and Gupta, 2021). Identifying the necessary capabilities for leveraging data analytics in IIoT settings is crucial to ensure its benefits are realized. This paper aims to identify and analyze the capabilities required for the successful implementation of data analytics in the Industrial Internet of Things (IIoT) setting to create business value. Specifically, the paper addresses the following research question:

Which capabilities are required for data analytics in IIoT environments to generate business value?

We approach this question by, first, identifying capabilities from the data analytics literature. Second, we investigate if and how these capabilities are relevant in the context of IIoT by conducting 16 expert interviews across 9 organizations.

The outline of the paper is as follows. Related work is discussed in Section 2. Section 3 describes the research methodology. The results of the expert interviews that led to the proposed framework of capabilities for data analytics in IIoT are presented and discussed in Section 4. Finally, Section 5 presents the conclusion.

2 Related work

The widespread popularity of IoT has led to the implementation of IoT technologies (such as radio frequency identification (RFID); wireless sensor networks (WSN), (Lee and Lee, 2015)) in different industrial sectors, like transportation, smart manufacturing, healthcare, retail, and utilities (Aamer et al., 2021, Elijah et al., 2018, Kamble et al., 2019, Sharma et al., 2020, Siow et al., 2018). IIoT applications are expected to yield many benefits for industrial companies such as enhanced operational processes, monitoring and controlling physical objects remotely, and improving visibility and flexibility (Kamble et al., 2019). Despite these potential benefits, the adoption and implementation of IoT are challenging as almost 75% of IoT projects are failing (Cisco, 2017). Prior studies have identified several challenges, such as lack of technical knowledge, lack of integration among IT networks, lack of interoperability, high operating costs, and security and privacy issues, that prevent organizations from realizing the potential benefits of IoT (Aamer et al., 2021, Elijah et al., 2018, Kamble et al., 2019, Sharma et al., 2020). Organizations, therefore, need to improve their ability to manage these issues in order to gain the benefits of IoT-generated data. As such data analytics tools can play an important role to analyse IoT data in order to reveal trends, unseen patterns, hidden correlations, and new information (Ahmed et al., 2017, Côrte-Real et al., 2020, Marjani et al., 2017, Rehman et al., 2019).

The importance of taking advantage of data analytics in the context of IIoT has gained a lot of attention in recent studies (Ahmed et al., 2017, Côrte-Real et al., 2020, Qi et al., 2023). However, to our knowledge, most of the previous studies concentrate on the technical aspect of IIoT analytics, disregarding how these tools create business value (Ahmed et al., 2017, Bashir and Gill, 2016, Marjani et al., 2017). For instance, Bashir and Gill (2016) develop an integrated IoT data analytics framework for the storage and analysis of real-time IoT sensor data. Ahmed et al. (2017), by conducting a comprehensive review, have developed a conceptual framework for analytics solutions for IoT. Some more recent studies strive to understand how the use of data analytics tools in the context of IoT can lead to competitive advantages. In this regard, for example, Côrte-Real et al. (2020) note that companies that do not develop capabilities to use IoT data effectively will be in trouble to create a sustainable competitive advantage. Then to understand the drivers and impacts of IoT and data analytics capabilities on firm performance, Côrte-Real et al. (2020) propose a conceptual framework and assessed it from a data quality viewpoint. Given that the concept of data analytics in IIoT environment is still evolving, there is a lack of research on identifying required capabilities. Prior studies described IIoT analytics capabilities on a high level of abstraction (Côrte-Real et al., 2020, De Vass et al., 2018) and no integrative frameworks have been proposed for identifying different IoT analytics capabilities and their effect on business value. Therefore, our study contributes to extending the knowledge of IoT analytics capabilities research by conducting explorative expert interviews (see more details in section 3).

To provide a theoretical basis for our investigation, we conducted a literature review in the related research field of data analytics capabilities. We utilized the Web of Science (WoS) database in our search to ensure a uniform level quality. We included journal papers written in English and published in the period from 2012 to 2021 with titles, abstracts, or keywords that matched our requirements. Our search resulted in 187 papers. We then screened the abstracts to identify those papers who directly contribute to our understanding of data analytics capabilities. From the selected articles we identified a set of 12 data analytics capabilities. We classify these capabilities into three main categories of technical, organizational, and human capabilities (Table 1) as proposed by Akter et al. (2016) and Wamba et al. (2017) . These core categories have also been used as a foundation in various other studies.

Main Category	Capability	Definition	References
Technology	Data Generation	The ability of organizations to seek, identify, create, and access data from heterogeneous data sources across organizational boundaries. This capability facilitates the data available to organizations by establishing procedures and policies to generate required data for decision-making	(Arunachalam et al., 2018, Işık et al., 2013)
	Data Integration	The ability to transform diverse types of data into a format that can be read and analyzed by analytics platforms, so that data is consistent, visible, accessible and interoperable.	(Arunachalam et al., 2018, Cosic et al., 2015, Işık et al., 2013, Jha et al., 2020, Ramakrishnan et al., 2020, Wang et al., 2018)
	Data Management and Security	The ability to manage data from different perspectives, such as data quality, flexibility, availability, and integrity, including the ability to ensure the data, networks, and systems are secure.	(Akter et al., 2016, Cosic et al., 2015, Ramakrishnan et al., 2020)
	Analytics Capability	The ability to drive decisions and actions through the extensive use of data and different analytical techniques, based on the specific mechanisms used for analytics, thus addressing the various needs of users and other stakeholders. Other important elements of this capability are user access, data visualization, and interpretation.	(Arunachalam et al., 2018, Cosic et al., 2015, Grover et al., 2018, Jha et al., 2020, Popovič et al., 2018, Wang et al., 2018)

Organizational	Planning and Investment	The ability to identify business opportunities, do cost-benefit analyses of data analytics initiatives, make investments, and determine how they can create business value.	(Akter et al., 2016, Cosic et al., 2015, Mikalef et al., 2018, Wamba et al., 2017)
	Process and Coordination	Represents a form of routine capability that structures the cross-functional synchronization of analytics activities across an organization and ensures processes are in place for each step in the project.	(Akter et al., 2016, Cosic et al., 2015, Ramakrishnan et al., 2020)
	Control	The ability to control functions, which are performed by ensuring proper commitment and utilization of resources, either implicit or explicit.	(Akter et al., 2016, Cosic et al., 2015, Rialti et al., 2019, Wamba et al., 2017)
	Data-driven Culture	The set of collective values, beliefs, norms, and principles that embrace and guide a data-driven culture.	(Arunachalam et al., 2018, Cosic et al., 2015, Gupta and George, 2016, Ramakrishnan et al., 2020, Wang et al., 2018)
Human	Technical Knowledge	The ability to understand technical knowledge elements, including operational systems, networks, programming languages, and database management systems.	(Akter et al., 2016, Cosic et al., 2015, Jha et al., 2020, Wamba et al., 2017)
	Business Knowledge	The ability to understand other business functions and the overall business environment. For example, analytics professionals can be nurtured to develop their feel for business issues and empathy for customers.	(Akter et al., 2016, Cisco, 2017, Rialti et al., 2019, Wamba et al., 2017)
	Relational Knowledge	The ability of analytics professionals to communicate and work with people from other business functions.	(Akter et al., 2016, Rialti et al., 2019, Wamba et al., 2017)
	Entrepreneurship and Innovation	The ability to mobilize and deploy data analytics functionalities to support innovation in the organization through infrastructure, and technological improvements.	(Cisco, 2017, Ramakrishnan et al., 2020)

Table 1. An overview of data analytics capabilities

Nonetheless, embracing data analytics in IIoT environments requires rethinking the relevance of the identified capabilities. The explorative research presented in this paper aims to understand if these data analytics capabilities are relevant in IIoT environments as well as to identify distinct capabilities for IIoT settings.

3 Methodology

Because this study is exploratory in nature, we adopted a qualitative research approach that involved conducting semi-structured interviews with experts. Semi-structured interviews are particularly appropriate for exploratory research since they provide an opportunity for researchers to engage in dialogue with respondents, enabling them to delve more deeply into specific concepts (Whiting, 2008). To select eligible experts to participate in this study four criteria are defined. First, the participants should have at least two years of experience with data analytics in IIoT environments, ensuring they have experience with IoT analytics. Second, the participants should have a high level of responsibility (like senior data engineer, IT manager, IoT solution architect), ensuring that they had a high level of understanding about the required capabilities and have expertise on technology levels. Third, the participants should have a higher education level, due to the abstractness of the subject. Fourth, participants should work in different industries (e.g., smart manufacturing, utilities, and logistics) (Siow et al., 2018)). This allowed us to capture multiple perspectives from different application domains of IoT analytics which in turn will enhance the generalizability of the findings. Using these criteria, we were able to identify and recruit 16 experts from nine different large organizations (employee size 1000^{+}) who were willing to participate in this study. Table 2 provides a summary of the participants.

To keep the inquiry-based conversation during the interview and to ensure the consistency of data collection across different interviews, we developed and used an interview protocol (available upon request). This protocol consisted of three parts: first, open questions about the participants and their experience of IoT analytics, the needed capabilities, and the business value from IoT analytics were asked. Second, each data analytics capability from table 1 was explained and discussed with the participants to evaluate its relevance in the context of IoT. In the closing part of the interview, by asking open questions, we inquired if any further capabilities have been experienced by the participants, which were not discussed.

Org.	Sector	Participant #	Participant responsibility	Participant role	Experience - Years	Education level
O1	Logistics	Exp_1	IoT Analytics	Senior Data Scientist	3,5	MSc Economics
		Exp_2	IoT Architecture	IoT Solution Architect	3	MSc Business & IT Management
O2	Smart Manufacturing	Exp_3	IoT Platform	IT Manager	11	MSc Information Technology
		Exp_4	IoT Architecture	Business Information Designer	10	BSc Managerial Economics
O3	Smart Manufacturing	Exp_5	IoT Platform	Connected Product Strategy	6	MSc Engineering
		Exp_6	IoT Analytics	Data Analyst	3,5	MSc data science
O4	Smart Manufacturing	Exp_7	IoT Analytics	Head of Data & AI	2,7	MSc Business Economics
		Exp_8	IoT Platform	Product Manager Digital Platform	2,9	MSc Product Design
O5	Utilities	Exp_9	IoT Architecture	Corporate enterprise architect	5^{+}	MSc IT – Asset Management
		Exp_10	IoT Platform	Chief Technology Officer	5^{+}	MSc Applied Physics
O6	Logistics	Exp_11	IoT Platform	Product Owner IoT	5^{+}	BSc Information Management
		Exp_12	IoT Analytics	Lead Data Scientist	2	MSc Mechanical Engineering
O7	Logistics	Exp_13	IoT Platform	Client Delivery Executive	2^{+}	MBA
		Exp_14	IoT Architecture	Senior Solution Architect	12^{+}	MSc IT Architecture
O8	Smart Manufacturing	Exp_15	IoT Analytics	Lead Data Scientist	$2{,}5^{+}$	PhD Mathematics
O9	Utilities	Exp_16	IoT Analytics	Innovator BI & Data Management	2^{+}	MSc Mechanical Engineering

Table 2. Profile of the selected experts

The interviews were conducted between 1 December 2021 and 20 May 2022. Each interview lasted between 60 and 90 minutes. We recorded and transcribed the interviews and sent them to the participants for verification. For data analysis, the transcription of each interview was read and coded by following coding process (Elo and Kyngäs, 2008). We engaged in open coding to label the raw data based on our questions, summarizing data into codes. Subsequently, we grouped similar codes to create categories. All coding was performed in Atlas.ti. To have an initial structure for the data analysis, Table 1 was used as a basis. However, besides the identified data analytics capabilities, we also looking for new IIoT capabilities. Newly identified capabilities were discussed by the research team to see if they can be considered as distinct IIoT capabilities, or whether they need to be considered as one of the already identified data analytics capabilities or splitting the existing ones.

4 Results and discussion

All 16 expert interviews went according to the plan. Participants highlighted the key differences between data analytics in IIoT and general data analytics, including the real-time and time-sensitive nature of IIoT data, the vast volume and diversity of data, and the resulting challenges in scalability, data management, quality, analytics, and cost management. For example, as noted by Exp_14 IIoT applications necessitate real-time streaming rather than batch processing. Exp_1 stated "*The critical* *aspect is the time-series component, where sensors capture timestamp, value, and unit of measurement... we must convert the time-series into segments, rather than a system of records with clear data table*".

In addition, we identified 24 capabilities required for data analytics in IIoT, based on 16 in-depth expert interviews. In accordance with the structure of table 1, these capabilities are classified into three overarching categories: technology, organization and human. The technology category encompasses 13 capabilities, while the organizational and human categories comprise seven and four capabilities, respectively. Further details on each of these categories are presented in the subsequent subsections.

In the following subsections, we will first present the results of the empirical study and then compare capabilities for data analytics in the IIoT with those of general data analytics. The focus of our discussion is on IIoT's new capabilities. Additionally, we incorporate relevant literature to support our arguments.

4.1 Technology capabilities category

Table 3 summarizes the 13 identified technology capabilities, including two generic data analytics capabilities applicable to IIoT, two subdivided capabilities, and six new IIoT-specific capabilities.

Expert interviews led to the division of **data management** and **security** into two separate capabilities. They noted that when data is transmitted from the edge, it must be stored, managed, and controlled, which is where IIoT data distinguishes itself from other types of data due to the vast amount of data generated from numerous systems and business units. Exp_4 stated that *the data comes in various file types, such as JSON, Parquet, and CSV, and requires several steps to trace back, process, structure, and store for reporting purposes*. Exp_5 emphasized *the complexity of balancing structured and unstructured data. Therefore, not only does data need to be managed for its intended purpose, but organizations must also focus on its governance structure to ensure data quality, integrity, and ownership*. As Exp_16 stated, *clear responsibilities, data owners, authorization, and data access rules are necessary*. Consequently, the term data management was revised to **data management and governance**. Interestingly, the literature on data analytics capabilities did not emphasize the significance of data governance. (Akter et al., 2016, Wamba et al., 2017).

The participants highlighted the significance of privacy, security, legislation, cybersecurity, and compliance with GDPR and local regulations in safeguarding organizations against potential threats in the context of IIoT. Consequently, **security and compliance** is considered a separate IIoT capability. This finding is in line with the increased security and compliance challenges mentioned in the IIoT literature (Arunachalam et al., 2018, Ramakrishnan et al., 2020, Sharma et al., 2020).

The participants suggested dividing the general analytics capability into **descriptive analytics and advanced analytics & automation** since many organizations have a dedicated Data Science team to enable more advanced IoT analytics. As noted by Exp_6, "*it's essential to differentiate between predictive and descriptive data analytics because they are two distinct things in terms of technology capabilities. if you have gigantic datasets from one or more products, then you do need that.* This was also explained as real-time analytics, which requires machine learning models to make short-term predictions. Next to that, several participants mentioned process automation. Exp_3 " *you can automate some physical things on the shopfloor, but you have to implement that locally. [With IoT] you can do that remotely*." In contrast to these findings, data analytics literature uses a general term of analytical capability and does not specifically allocate varying levels of capabilities for each type of analytics (Grover et al., 2018, Wang et al., 2018).

Participants emphasized that an **IIoT platform architecture and design** capability is crucial for implementing data analytics in the IIoT context. Exp_9 stated *"you do not build a single-purpose IoT solution. You build an IoT chain, that's very difficult because a lot of vendors offer siloed solutions.* A deliberately architected IIoT platform, primarily on cloud technologies, is necessary to determine required data, ensure the robustness and scalability of IoT solutions and use cases, and enable seamless integration of cyber-physical interface in IoT devices (Kamble et al., 2019).

Example Quotes	Capabilities	Definition
EXP_2: *With IoT Analytics we talk almost always about time-series data which is all generated by different machines and sensors that work across our different terminals. Being able to generate real-time events, as we have a lot of robots and sensors.* **Exp_4:** *With IoT, it's real-time or near real-time data. You really need [to be capable of] the collection [and generation] of data at the edge [machines/shopfloor],* **Exp_15:** *we have 30+ sites and every site is different, Now we have around 500 to 1000 sensors. So you shouldn't underestimate that data acquisition [generation].*	Data Generation	The ability to collect and generate real-time or near real-time data based on measurements from the hardware and sensors at the edge. This includes the ability to capture time-series data from different sources such as connected devices, sensors, robots, machines, and operational systems.
EXP_1: *you want to have a complete view of what is happening in the process, so you need to see the time series data in the context of asset, and production order data. And this data sits in different places as we have 60- 70 terminals, and you want to be able to view that data integrally.* **EXP_4:** *with analytics, you need to combine data streams, so in our case data from Aspentech. Then you get the data values of production lines at that moment, but that data doesn't say much in itself because you don't know what product is produced. as data coming from different systems it needs to be combined. That can be a challenge and that has to do with integration between systems.*	Data and Systems Integration	The ability to connect, integrate, and combine data streams from different IoT devices, business applications, and legacy operating systems to provide a comprehensive view of what is happening and ensure interoperability across all business units in an industrial environment. This involves integrating different machines, sensors, devices, and systems to create a cohesive network that can communicate and share data seamlessly.
Exp_5: *A lot of data in hot storage, that's easy and you get easily developed against that, but it costs a lot. On cold storage you need to look at it completely different. So you really need to be able to find that balance, structured data, unstructured data, and the amount of it. I think that's the complexity behind IIoT* **Exp_7:** *The cost component becomes an increasingly important factor, while with transactional data you often think the more data the better. But with IoT, it just becomes too expensive to store all that data. Processing real-time data, storing it, visualizing it, analyzing, data management, APIs and to bring structure to IoT data, requires a lot more work and thought than in more transactional data.* ***Exp_15:*** *we notice that the sensors are often quite good and new, but there's a local outdated system in between which is badly maintained, unstructured data is just thrown into it. So that has been one of our largest bottlenecks.*	Data Management & Governance	The ability to effectively organize, store, process, validate, and govern (includes data policies, security regulations, procedures, and standards) data that is generated from various sources and in different formats while ensuring its quality, accuracy, and accessibility for analytics and reporting purposes. It involves managing structured and unstructured data from IoT devices, ERP, CRM, and other systems. In IIoT settings, data management and governance entail the utilization of suitable tools and technologies for storing, processing and analyzing data, such as data lakes
Exp_9: *for example all those connected devices in smart energy solutions send data to the cloud, so cybersecurity is very important for our IoT analytics projects. If we would not have worked on the security part for instance in our current project on virtual power plant for energy trade, we would have been off the market after two weeks.* **Exp_13**: *we are generating data from 90,000 products and will add 230,000 products, it's an immense amount of data that is constantly generated. as it's stored in a data lake you have to keep a close eye on privacy, security, and legislation.* **Exp_14**: *To ensure the continuous operation of our global logistics enterprise, we require 24/7 security protection against potential threats. We must ensure that our data processing activities are GDPR compliant and adhere to local regulations in the various countries where we operate.*	* Security & Compliance	The ability to protect and secure the vast amount of data generated by industrial devices and objects, to protect critical infrastructure, and devices from unauthorized access, cyber-attacks, and other security threats to ensure the safe and reliable operation of IIoT systems, as well as compliance with privacy, security, and legislation standards, including GDPR and local regulations when implementing IIoT systems.
Exp_3: *you can automate some things on the shop floor, [With IoT] you can do that remotely from your home and change things. Or even you can automate with Machine Learning with cloud services so that for example when the temperature increases, do something on-site like reduce speed or rotation.* **Exp_5:** *we collect and move, since 2016, data from our [products] into a cloud. we have had two-way communication with the [product] since 2020. So that enabled us for example geofencing, telling the [product] how it should behave based on its location. Now we are making our first steps toward predictive and prescriptive maintenance.* **Exp_15:** *we developed a machine learning model (to make predictive maintenance) but then we found out that the registration of downtime and reasons for downtime, was not up to date at all and not specific enough. They did it on a daily basis instead of per minute or even per second so we couldn't use that to properly train the model.*	* Advanced analytics (predictive, prescriptive) & Automation	Advanced analytics capability refers to the use of advanced statistical and mathematical models and algorithms to analyze large amounts of data generated by IoT devices, industrial processes, and equipment. In an IIoT setting, automation capability allows for remote control and automation of processes, even from a home setting. This can be achieved through the use of IoT sensors that collect real-time data, machine learning algorithms that analyze the data, and cloud services that provide remote control and automation capabilities.
Exp_3: *From an operational view, we have descriptive analytics that enables us to understand what is happening in the production process of plastic materials on a very detailed level [data temperature] and see if there are any anomalies.* **Exp_5:** *That is very operational; descriptive analytics [BI] helps us to gain insights on how is the usage of a [product] and an operation, how much consumption we get out of it, and the average speed, we also do a lot of reporting and also share these reports with the customers.*	* Descriptive analytics	The ability to analyze and interpret historical data from industrial machines, devices, and sensors to identify patterns, trends, and insights into the performance of industrial equipment and processes to optimize resource usage. It can also be used to monitor the health of equipment and identify anomalies.
Exp_11: *You also need tee capability to determine per use case which technological solution the correct one is. Are we using a tracker with a SIM card, are we using a beacon, are we doing things with LoRa, with Zigbee. All of those have advantages*	** IIoT platform architecture and design	The ability to design and architect an IIoT platform by incorporating different types of devices and sensors, to handle large volumes of data, provide real-time processing and analytics, and integrate with

and disadvantages. So you need the capability to determine what will be your solution design. We run on AWS IoT services, so we are running on a serverless platform, which is immensely scalable. **Exp_13:** *We are now rebuilding that whole IoT platform, and I am responsible for the service level agreement, the implementation, and the telecom solution to develop the communication between the products and the platform. But also, on the M2M (machine to machine). we have made the conscious decision to move this new IoT platform to a cloud platform in Azure.* **Exp_14:** *for example within the cloud platform stack, we try to build cloud agnostic as much as possible, to be able to switch easily between cloud platforms if needed.*		other systems and applications in an industrial setting. The IIoT platform should be capable of handling multiple use cases. The architecture of IIoT should be designed to be scalable and flexible, using cloud-based services that can handle large amounts of data and provide real-time analysis and insights. The system should also be designed to be bidirectional, allowing for the transmission of data and commands in real time.
Exp_2: *An example is that on one terminal we have 1200 manual [assets], where we have no insights. Eventually, we developed sensors [which communicate with LoRa] for these assets to implement status notifiers.* **Exp_6:** *the capabilities that we need now for the state of health analytics, are embedded in our data warehouse solution, Azure Synapse. That allows us to collaboratively, with PySpark, do analyses on our raw data. We often request 5 years of data about a product that logs data per second, which we need for building our machine learning algorithms. So we need to be able to work with large datasets, and that's where distributed computing helps us.* **Exp_15**: *We have a multitude of robots and sensors that transmit continuous data,. we have 500 to 1000 sensors, and data retrieval must occur every 2 minutes to avoid system failure.*	** Edge & hardware development	The ability to build and deploy computing infrastructure and hardware components, such as sensors, gateways, and controllers that are optimized for processing and analyzing data that are specifically tailored for IIoT use cases.
Exp_11: *we want to manage our logistics with a more data-driven approach, so we developed an IoT platform from scratch, without any packaged software. We run on AWS IoT services, so we are running on a serverless platform, which is immensely scalable. This capability for us is very relevant.* ***Exp_14:*** *you have a stream of IoT messages, and you parse it, in our case we set the results in a data mart. And the reports and events functionality in the platform is based on the data in the data mart, or the events that are generated from real-time processing. we have functionality that enables the customers to choose whether or not the data is collected and analyzed in the cloud.*	** Software development	The ability to develop and maintain software applications that enable the collection, analysis, and transmission of data between industrial devices, machines, and systems. It involves using various programming languages, and tools to create software solutions that can integrate with different IIoT platforms. It also includes the ability to build scalable and reliable software systems that are capable of handling large volumes of IoT data in industrial settings.
Exp_3: *Regarding analytics part, the connectivity is the key. the 5G technologies, will enable more speed to transfer IIoT data.* **Exp_5:** *we collect and move, since 2016, data from our [product] into a cloud environment, I think it starts with connectivity.* **Exp_7:** *we deal with it a lot…when messages arrive, is the network connectivity good, setting it up and connecting devices and robots, the question is how you prioritize the different devices and sensors in the connectivity.* **Exp_10:** *has an event streaming platform based on Kafka, so we deliver data there. We also make data available through APIs and we also deal with data in data lakes.*	** Connectivity	The ability to establish and maintain reliable connections between various devices and systems such as machines, devices, and sensors, within an industrial environment to enable seamless data exchange and communication between devices and systems. In IIoT settings, connectivity is essential for generating and transferring data to a cloud environment or IoT hub for processing and analysis.
Exp_1: *Every four hours we got an enormous dump from local FTP servers, which would end up in a cloud. But then you had many ZIP files with files in them which I then had to read out and transform. And that you need to replace through a query to get for example all the time-series for a certain asset. Or if I query data from different systems in [location A] or from [location B], it should be available in the same format.* **Exp_4**: *With IoT it's also real-time or near real-time data, so you need [capable of] processing it in the cloud. I think about 70% we spent on extracting and formatting the data and 20 to 30% we spent on analytics.* **Exp_8**: *in our case the robots and embedded software is not standardized. So a piece of code is different from robot to robot,*	** IIoT data processing & standardization	The ability to collect, process, and transform data generated by various (operating technology)OT systems, devices, and sensors, from the edge to the cloud, into a standardized format and make it available for analytics and intelligence applications to derive meaningful insights from industrial processes. It also includes the ability to handle missing or incomplete data, and the need to process and analyze large amounts of data in (near) real-time.
Exp_7: *Operationally, the question is how everything can keep running properly. how we ensure the uptime and performance of robots? checking incidents on the robots, so looking at the logs – real-time monitoring, is the data stream working.* **Exp_13:** *"we need to be able to keep the whole system alive 24/7. you need to be able to do monitoring, which keeps track of that infrastructure, whether or not all your integrations points are still available* **Exp_16:** *What happens when the server goes down, how do they understand that it is going wrong and what is going wrong. So we needed to build in several checks because you don't want to lose data in our in factories.*	** Operational maintenance and monitoring	The ability to monitor and maintain industrial equipment, processes, and systems in real-time to ensure the proper functioning of connected devices and systems. This involves real-time monitoring, checking incident logs, tracking equipment health, analyzing behavior, and receiving alerts when things go wrong.
Exp_12*: you need to be able to access your data. There needs to be a difference between the historical data and analytics and the real-time data and analytics. They should never hinder each other, but I do see that happening. That you get write errors because someone is applying heavy analytics on the same data. It needs to be both accessible and fast.* **Exp_16:** *You need to be able to make data accessible and available to the organization, that needs to be done with a certain frequency where the data quality is good.*	** Data Accessibility	The ability to easily access and retrieve data generated by various devices and sensors. It involves providing tools and APIs that enable authorized users and analysts to access data quickly and easily

*Table 3. Technology category (*Compared to table 1, (*): capability that is split; (-): a modified capability,(**): a new capability that is specific for IIoT)

Moreover, the value of this architecture capability results in an abstract layer on which one can build different use cases, instead of a single-purpose application that one builds or buys. Exp_11 mentioned "*you need a capability to determine what will be your solution design. and the Enterprise Architecture behind that."* However, we could not find any evidence on such a platform architecture & design capability in the data analytics capability literature, possibly because IIoT is viewed as a more comprehensive and strategic initiative.

In contrast to data analytics capabilities, the participants identified two novel capabilities crucial to IIoT: **edge & hardware development**, and **software development**. As noted by Exp_13 " *you need to understand that there's a lot of software running in that product and there are so many parts that are connected. so you need that capability."* Many organizations have investigated hardware development capability to enable an IoT environment. Additionally, organizations must address the placement and management of hardware at the edge. According to Exp_9 "*what's different for IoT a lot of capabilities for IoT play out at the edge*". This means organizations will need to have access to operational technology, to embed the IIoT hardware into the operational setting. Exp_ 7 stated, "*we have discussions about topics like on-edge deployment. How can we develop models in the cloud, deploy that on-edge*". Exp_12 echoed this notion.

The participants frequently cited **connectivity** as a distinct capability of IIoT, ensuring that data is almost instantly available. Connectivity is arguably the most distinctive capability of IIoT, ensuring connectivity between the edge and among devices. Exp_9 stated that" *being able to connect a lot of IoT edges [devices], that's the capability."* Exp_14 said, *"You need to be able to configure network connectivity".* Recent studies also confirm the importance of connectivity. IIoT should be fault-tolerant and should not depend solely on continuous access to the Internet or cloud. As a consequence, IIoT must operate autonomously and remain fully functional even during network interruptions (Qi et al., 2023). To address the connectivity challenges in IIoT, Boyes et al. (2018) conducted a study to identify the critical components of the networking or communication connectivity between the device and the IIoT system in which it functions.

Although the experts who partook in our study had knowledge of the potential opportunities for IIoT data analytics and experience in this area, they acknowledged that the path towards it is not without challenges. The participants highlighted that as IIoT data comes from diverse sources with varying dimensions, features, and formats, **data processing and standardization** is crucial to ensure accurate processing and standardization before storage. Failure to do so would make it impossible to correlate and analyze IIoT data. Exp_7 noted" *IoT generates mainly logs and dumps a lot of information, I think being able to process IoT event logs, the real-time component, the order and sequencing of it, being able to prioritize different data, and being able to process it, and bring structure to IoT data, that for me is the largest difference from transactional data; data processing and how to manage all that and standardize*." Standardization is required for the successful implementation of data analytics in the context of IIoT as a lack of standardization causes difficulty in interoperability and the exchange of data among different IoT devices (Sharma et al., 2020). However, IoT landscape still lacks a unified standardization to allow communication and integration between heterogeneous IoT devices and networks (Diène et al., 2020).

To most of the participants in the study, having **operational maintenance and monitoring** capability is deemed essential for IIoT, as emphasized by Exp_8 the need to monitor IIoT platforms, from hardware and connectivity to the data itself. Exp_9 stated that "*we have an operating control center, and in that we monitor 24/7 everything that is connected*". Exp_11 added that monitoring the quality of service of IoT is also a major difference due to the physical environment that needs to be checked to ensure data validity and reliability. Given the need to integrate and execute data from diverse online and offline, inbound and outbound operations, deploying, maintaining and monitoring processes for IoT systems require significant effort (Rehman et al., 2019).

The participants in our study identified **data accessibility** as another essential capability for IIoT. To derive value from IIoT data, date needs to be accessible to authorized users and applications. The participants suggested using tools such as APIs to enable data accessibility. Exp_5 emphasized the importance of accessibility, stating that it is a key factor in the success of data analytics efforts in IIoT. Incorporating access control mechanisms in IIoT environments is regarded as a challenging task, primarily due to the diverse range of technologies and protocols employed in IIoT networks and devices (Salonikias et al., 2019).

4.2 Organizational capabilities category

Table 4 illustrates a total of seven organizational capabilities for data analytics in IIoT.

Capability	Definition
* IIoT planning & scalability	The ability to of an organization to plan and execute IIoT projects in a strategic manner that ensures scalability and extensibility of the infrastructure. The scalability aspect of IIoT planning refers to the ability to manage fast incoming complex data, process and store data efficiently, and analyze large amounts of real-time data.
* Business-driven IIoT strategy	An organization's ability to operationalize top management vision for IIoT, develop a comprehensive IIoT strategy that aligns with business goals. It involves identifying specific areas of focus, prioritizing investments, and creating a long-term vision of the role of IIoT technologies and systems within the organization. the success of a business-driven IIoT strategy is dependent on the organization's ability to effectively communicate the value of IIoT initiatives and secure investment from key stakeholders.
Process and Coordination	An organization's ability to manage IIoT projects in a structured, coordinated, and agile manner. This includes the ability to define and develop processes for managing IoT projects, establish standards and prerequisites, and ensure that goals are scoped properly. It also requires having agile proof of concept and pilot projects before globally rolling out IoT projects.
- Change Management	The ability to drive change in the organization internally but also potentially in the rest of the ecosystem of customers and partners through close collaboration, clear communication, and simply investing time and resources.
** Knowledge Management & Training	The ability to attain, record, maintain, and share knowledge concerning IIoT Analytics and train and enable all stakeholders involved in the IIoT analytics initiative, both internally and externally
** Business and ecosystem synergy	The ability to synergize business units and teams in the IIoT Analytics initiative, as well as the wider IoT ecosystem including customers and partners, to strengthen the required IIoT Analytics capabilities or close any capability gaps.
** Product & service development	The ability to develop products and services with a fully integrated Internet of Things, generating data that is transformed into insights or actions for internal and external users.

(Compared to table 1, (*): capability that is split; (-): a modified capability,(**): a new capability that is specific for IIoT)

Table 4. Organizational category - Capabilities for data analytics in IIoT

The analysis of expert interviews lead to splitting the planning and investment capability (table 1) into two discrete capabilities; **planning & scalability**, **business-driven IIoT strategy** (table 4). All participants noted that scaling is key to driving IIoT analytics business value. As they mentioned the abundance of opportunities is one of the challenges of IIoT analytics, which necessitates a capability to plan, create a roadmap, and scale proven concepts. Therefore, having planning and scalability for IIoT becomes especially important when scaling use cases across multiple processes, sites, or products. Exp_8 stated, "*The opportunities are endless, scoping, resources, so the main question is what do you do first, prioritizing, and creating a roadmap*." Without planning there is no scaling, and without scaling there is less planning needed. Moreover, having a clear vision, together with a business-driven IIoT strategy are critical to gain strategic value from IIoT analytics initiatives. Exp_ 4: " *You need to know where you're going with your IoT analytics initiative. The organization needs to have a vision for that*." Exp_ 12: " *if the organization has a clear long-term view is really helpful because then you can much better find the right IoT that fits within that vision*."

Not surprisingly, due to the novelties and ambiguities of analytics in the context of IIoT, many people are scared that it will take over their job. So **change management** capability is very important for the success of IIoT analytics as you need to convince people. As stated by Exp_12, *you need to effectively communicate to your organization what you will do with IIoT and the data, and what impact it will have*. While this capability was initially named data-driven culture, the participants suggest that change management better reflects what organizations need.

Participants revealed that one of the important capabilities for analytics in the context of IIoT is **knowledge management** and **training** as IIoT analytics is a knowledge-intensive venture which is very specific and new to many organizations. Exp_ 5"*securing IIoT analytics knowledge is very important, so as not to have it only available in the heads of a few specialists but more broadly accessibility*." Once that knowledge is attained, it is important to maintain and share that within the organization. It is important to differentiate between this capability and skill & knowledge capability falls under human capabilities because knowledge management capability relates to the organizational capability of attaining and maintaining IIoT analytics knowledge in the organization.

One of the major challenges of IIoT analytics for organizations is the need to collaborate externally, as they may not be able to manage everything on their own. This often requires the integration of internal and external silos which demands external collaboration. For instance, Exp_ 1 stated: "*We have a cloud partner who helps us with the cloud platforms.*" Exp_6 noted: "*we try to do a lot in-house, and if we cannot do it yet, we do it with partners, which allows us to be more efficient.*" Therefore, **business and ecosystem synergy** was identified as a new IIoT capability. Exp_9 *"It is a huge undertaking to align with all stakeholders on the outcomes of IoT data analytics. That's not so much technical, but more organizational, to agree on that."*

Finally, new **product and service development** based on IIoT data was seen by almost all participants as an important IoT analytics capability, as one of the main goals for IoT analytics is to productize the data. Exp_9 "*The first capability that we needed was good product development* ". By developing new IoT-data- based services, organizations enable to offer an integrated proposition (a combination of their original product and smart IIoT services as well as to create a glue layer between the different organizational departments (Exp_9).

4.3 Human capabilities category

Analysis of the human category data has demonstrated the relevance of all four human capabilities outlined in table 1 for IoT analytics capabilities (table 5). In this category, three capabilities from table have been modified.

Capability	Definition
- IIoT Technical Skills & Knowledge	Set of technical skills and knowledge ranging from hardware knowledge to specific knowledge about hardware and operational technology, networking, data processing tools, databases, data structures, cloud computing, and Understanding of industry-specific regulations and compliance requirements to design, develop, deploy, and maintain IIoT systems.
- IIoT business Skills & Knowledge	the ability to understand and integrate the technical aspects of IIoT with the business goals and processes of an organization. This capability requires a combination of technical skills and knowledge, such as programming and data analysis, with soft skills, such as communication, collaboration, and leadership. It involves understanding the questions and needs of customers and stakeholders, knowing what data and metrics are needed to improve processes and products, and being able to effectively communicate the value and impact of IIoT solutions.
- Interdisciplinary collaboration	The ability to collaborate across disciplines and domains with subject matter experts and understand each other's goals and challenges. This is instrumental in building the right business cases and aligning the technological implementation with those business cases.
Entrepreneurship & Innovation	The ability to see potential and opportunities in IIoT technologies. It requires individuals who can sell the concept of IIoT to higher management, convincing them of the added value of IIoT. Entrepreneurship skills are necessary to balance small projects and large ambitions to develop creative solutions based on strong business cases.

(Compared to table 1, (*): capability that is split; (-): a modified capability,(**): a new capability that is specific for IIoT)

Table 5. Human category- Capabilities for data analytics in IIoT

As data analytics initiatives in the context of IIoT are highly technical by nature, many participants found that specialized **technical knowledge and skill** are required to work with IIoT data. Exp_6 noticed "*I see IoT as something that indeed requires specific knowledge. So, having knowledge of cloud, data processing, data storage, IoT, software, hardware, and knowledge about our product is necessary for doing IoT analytics*." Besides IIoT technical skills and knowledge, technical people must be able to translate business needs into technological solutions. Therefore, business skills & knowledge were stated by the participant as one of the relevant and important IoT analytics capabilities. Exp_2 stated, "*without any business knowledge, well... that doesn't lead to good solutions.*" This capability includes many soft skills and knowledge such as strong communication, presentation, and management of IoT analytics programs to align processes and people. The last capability of this category is interdisciplinary collaboration capability. Often data analytics is engrained in critical business processes, such as production, logistics, and supply chain. Therefore, the variety of people working on such processes and the information involved are often greater than in general data analytics projects. This challenge requires a strong interdisciplinary collaboration capability as stated by Exp_1 "*We determine together with the terminal team […] which decisions from your side are we going to automate, or support, that's where the collaboration starts. A good relationship with the domains that you deal with to understand the context well enough*."

4.4 Capabilities and Business Value of Data Analytics in the IIoT

The identified 24 capabilities for data analytics in the IIoT environments have the potential to generate two types of business value: strategic and operational. As IIoT is integrated into vital business processes, the operational business value tends to take precedence. The participants in the study emphasized that organizations are primarily interested in investing in analytics to gain real-time insights through visualizations and dashboards, and subsequently to achieve operational excellence via advanced use of IoT data and automation. Drawing from both the review of data analytics capabilities literature and the empirical data analysis in the IIoT context, a unified framework that encompasses capabilities for data analytics in the IIoT and the resulting business value is presented in Figure 1.

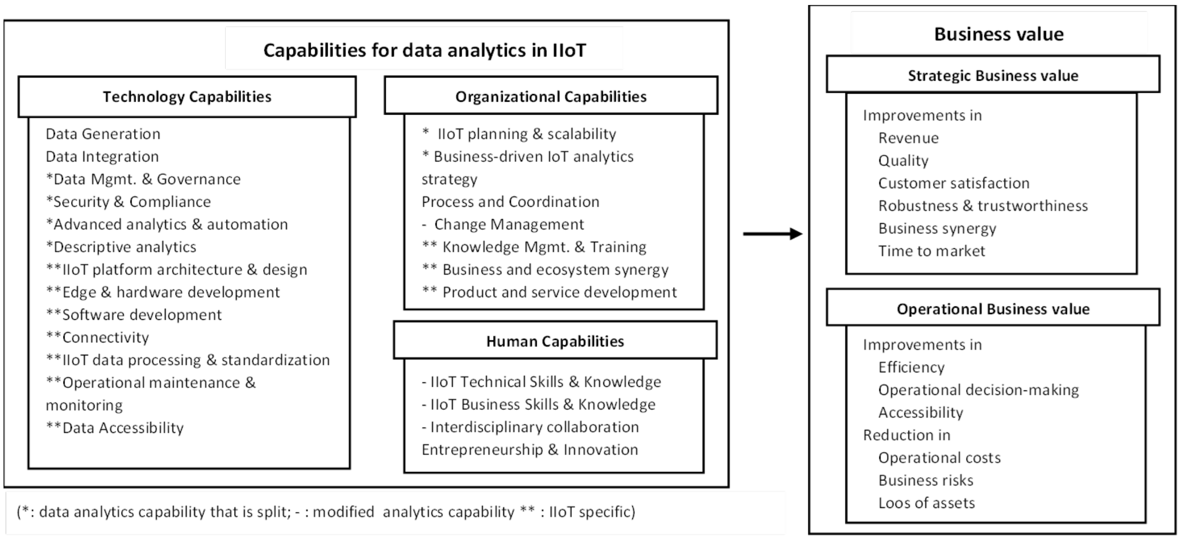

Figure 1. A integrative framework of capabilities and business value of data analytics in the IIoT

5 Conclusion

By investigating the differences between generic data analytics (Table 1) and capabilities required for the successful implementation of data analytics in the IIoT setting (Tables 3-5), this study shows that generic data analytics capabilities can largely be transferred to the context of IIoT. One major observation, however, is that data analytics in the context of IIoT is challenging because of the novel and often complex characteristics of IIoT that can give rise to specific data-related issues. For instance, IIoT systems require real-time data processing capabilities to ensure that decisions are made quickly and accurately. This can be a challenge when dealing with large volumes of data and when there are strict latency requirements.

In this study, we identify the capabilities required for IIoT data analytics by conducting 16 expert interviews from nine big industrial companies operating in the logistics, smart manufacturing, and utility sectors, that use IIoT technologies and implement data analytics within the IIoT context. We identify a set of 24 capabilities including ten unique IIoT capabilities: IIoT platform architecture & design, Edge & hardware development, Software development, Connectivity, IIoT data processing & standardization, Operational maintenance & monitoring, Data accessibility, Knowledge management & training, Business and ecosystem synergy, Product and service development.
Our work has a two-fold contribution to the IIoT literature. Firstly, we enrich the existing knowledge of data analytics in the IIoT context by identifying a set of capabilities that are imperative for the implementation of data analytics. We also analyze how these capabilities impact firm performance, resulting in a practical yet theoretically grounded framework of integrative capabilities and business values of data analytics in IIoT. This framework comprises 24 capabilities and encompasses both strategic and operational business values. Secondly, we also identify and discuss 10 capabilities that are specific to IIoT, highlighting the unique requirements for data analytics in this domain that differ from those of generic data analytics capabilities. By distinguishing these capabilities, we provide a more nuanced understanding of the distinctive needs of data analytics in the context of IIoT.

Practitioners can benefit from this study in three ways. Firstly, the study highlights the differences between generic data analytics and analytics in the context of IIoT. This indicates that practitioners need to deal with unprecedented levels of complexity and scale, as well as gain new and specific knowledge about potentially unique technologies in the IIoT context. Secondly, the proposed framework can assist organizations in dealing with the uncertainties and complexities often involved in IIoT and analytics projects, enabling them to develop a comprehensive plan and identify the appropriate business goals for analytics initiatives in the IIoT context. It is crucial for organizations to understand that, in addition to generic data analytics capabilities, a range of technical and organizational capabilities specific to IIoT is required for the successful implementation of data analytics initiatives. Thirdly, the skills and knowledge required to implement data analytics in the IIoT context should not be underestimated. Furthermore, managers must realize that data analytics in the IIoT context necessitates a long-term and pragmatic vision, which can facilitate the organization's transition towards a more integrated future.

This study is constrained by a number of limitations that open an avenue for future research. First, while our attempt is to provide a structured overview of the literature on data analytics capabilities, due to potential bias in the coverage of the literature, we do not claim that a list of data analytics capabilities is complete. Future research may expand on this list. Second, we interviewed 16 experts from nine big industrial companies. Although our purposive sampling approach involved a cross-organizational and cross-industry sample, we acknowledge that it may not have fully captured the potential specificities of companies or industries. Nevertheless, this strategy helped us minimize bias and achieve a certain level of confidence in the generalizability of our findings to companies operating in logistics, smart manufacturing, and utility sectors and implementing data analytics in the context of IIoT. However, the generalizability of our findings to other industries may require further research. Third, this research is a first step towards understanding business value creation through data analytics in the context of IIoT from the theoretical lens of capabilities. Therefore, the contribution of this study is largely explorative. Our claim is not that the proposed framework is complete but rather that it provides a basis for further empirical investigation and validation. Fourth, specific IIoT capabilities from our expert interviews may be subject to the personal bias of the interviewees. They might have a different understanding of capabilities or do not have complete knowledge of the capabilities required for data analytics in IIoT settings. We undertook considerable efforts to at least partially mitigated this problem, for instance, by providing interviewees with the definition of each data analytics capability (from table 1) as well as interviewing multiple experts from the same industries. Interviewing multiple respondents within a single organization would be useful to improve internal validity. Finally, the proposed framework can serve as a valuable starting point for understanding capabilities required for analytics in the IIoT context. Nevertheless, our exploratory study did not examine the impact of each capability on strategic and operational business value. Future explanatory studies should investigate the interrelationships and linkages between these capabilities and business value.

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