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DOI
10.5220/0006296300700079

Publication date
2017

Document Version
Final published version

Published in
Conference: IoTBDS, 2nd International Conference on IoT, Big Data and Security

Factors Influencing Adoption of IoT for Data-Driven Decision Making in Asset Management Organizations

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Keywords: IoT, Internet of Things, Asset Management, Data Governance, Decision Making.

Abstract: Organizations tasked with managing large scale, public civil infrastructure are increasingly looking at data to drive their asset management decision-making processes. The Internet of Things (IoT) enables the creation of data that can be used to gain further insights into the current and predicted state of the infrastructure and may help automate the asset management process. Yet, it remains unclear to what extent data from IoT impacts decision-making in public asset management organizations. The objective of this paper is to explore implementation factors for adoption of new data sources for decision-making in asset management organizations. Based on a systematic literature review and case studies in the asset management domain, this paper derives the current use and expectations of new data sources for decision-making in asset management. The paper concludes that although recent technological developments have enabled the deployment of IoT for asset management, the current level of adoption remains low. The inherent complexity of adopting a data-driven approach to asset management requires an effective data governance strategy to ensure data quality, manage expectations, build trust and integrate IoT data in decision-making processes.

1 INTRODUCTION

Many organizations tasked with managing civil infrastructure routinely store large volumes of data. More and more, new sources provide this data for producing and collecting real world data that can be communicated on the internet, such as sensor devices, social media, and user-generated data (Barnaghi, Sheth and Henson, 2013). When these resources communicate and are integrated, many physical objects are able to act in unison, by means of ambient intelligence (Ramos, Augusto and Shapiro, 2008). The object becomes a part of a complex system in which the whole is greater than the sum of its parts (Miller and Page, 2009). The Internet of Things (IoT) describes a situation whereby physical objects are connected to the Internet and are able to communicate with, and identify themselves to, other devices (Atzori, Iera and Morabito, 2010). For example, this may include GPS-based navigation applications for smartphones based on real-time traffic information shared by other drivers, or real-time weather service based on the information updated by sensors of users' smartphones or weather radars and other weather observation tools (Zhang *et al*., 2015).

This research takes place in the asset management domain of large scale civil infrastructure. Asset management (AM) is important for this industry as the success of an enterprise often depends on its ability to use and manage its assets efficiently (Koronios, Lin and Gao, 2005) and effectively (Schraven, Hartmann, & Dewulf, 2011). AM is a discipline for optimizing and applying strategies related to work planning decisions in order to effectively and efficiently meet the desired objective (Mohseni, 2003; Mathew, Ma and Hargreaves, 2008; Hastings, 2010).

IoT is important to AM because an object that can communicate digitally also becomes connected to surrounding objects and data infrastructures. For example, it is possible to determine the position and length of traffic jams, and to monitor trends, variations, and relationships in the road network over time using smartphone data, networked sensors and cameras to analyze traffic flow (Brous and Janssen, 2015b). But in order for IoT data to be accepted by asset managers, a variety of barriers such as trust and acceptance still need to be overcome (Brous and Janssen, 2015a). The concept of trust is often used in various contexts and with different meanings. Trust is a complex notion which is hard to define, although its importance in data-driven decision-making is widely recognized (Sicari *et al.*, 2015).

IoT devices and the communication between these devices may benefit the management of civil infrastructures by providing enough quality data to generate trusted information required to make the right decisions at the right time (Brous and Janssen, 2015b), helping organizations improve their decision making capability. However, the quality of this data has been seen to vary greatly over time (Barnaghi, Sheth and Henson, 2013). Trusted data is regarded as essential to aiding the decision-making process in asset management (Haider, Koronios and Quirchmayr, 2006). Having trusted data is therefore essential for organizations which have data driven decision making processes.

IoT data can vary widely in format and representation, and determining the quality of data is important to allow asset managers to trust IoT data, especially in use-case scenarios where the data is made available by a large number of different providers (Barnaghi, Sheth and Henson, 2013). The satisfaction of trust requirements is often related to identity management and access control (Sicari *et al.*, 2015), and as real world data can be related to people, privacy and security are also key concerns (Barnaghi, Sheth and Henson, 2013). The challenge is greater when the scale of the data and the number of different parties that can access and process the data increase.

It is often assumed that public organizations are well equipped to handle data, but this is not always the case (Thompson, Ravindran and Nicosia, 2015). The objective of the paper is therefore to explore conditions and factors for effective and sustainable adoption of new data sources for decision-making in asset management organizations. Data management is complex and it is difficult to understand and assess the issues surrounding this process (Grus, Crompvoets and Bregt, 2010). It can be difficult to attribute success or failure of data management projects to one or more specific factors. Because data management is complex, there is an interrelationship between the sociological and technical dimensions of data management, and it is difficult to track cause-and-effect relationships (Brous, Herder and Janssen, 2015).

Data management issues often do not arise from existing business rules or the technology itself, but from a lack of sound data governance (Thompson, Ravindran and Nicosia, 2015). Data governance has recently received wide-spread attention from practitioners as organizations are becoming increasingly serious about the notion of “data as an asset”. Data governance is about identifying the fundamental decisions regarding data that need to be made and who should be making them (Khatri and Brown, 2010).

The methodology used in this research is described in section two. In section three a systematic review of literature derives the current potential of IoT data. In section four, two explorative case studies of asset management projects in The Netherlands describe the current uses and expectations of IoT data. The results of the literature review and the case studies is discussed in section five. The results show that IoT data has a variety of potential uses and that expectations are high, but asset managers remain unconvinced, and adoption of IoT data for decision-making in asset management remains low. Conclusions are drawn in section six.

2 METHODS

This article follows the literature review method proposed by Webster and Watson (2002) and attempts to methodologically analyze and synthesize literature regarding the potential uses of IoT data in asset management. It will advance the knowledge base of data-driven decision-making in asset management by deriving the current uses of IoT data for asset management that can be used by researchers to focus on important data management issues, and by practitioners to develop an effective data management strategy and approach.

There is only limited research on the management of IoT data, and perceived expectations compared with the actual usage of IoT data for decision-making in asset management organizations. The keywords: “infrastructure”, “IoT” or “Internet of Things”, “data”, and “use” returned 324 hits within the databases Scopus, Web of Science, IEEE explore, and JSTOR. 294 hits were journal articles, 29 were conference papers and 1 hit was a book. We then filtered these results and performed a forward and backward search to select relevant articles based on the criteria whether they included a theoretical discussion on the use of IoT data in asset management decision-making. Based on this forward and backward search, 30 journal articles, and conference proceedings were selected and relevant principles from these sources were listed.

The cases under study occur within the asset management process of the Directorate General of

Public Works and Water Management of The Netherlands. The Directorate General of Public Works and Water Management of The Netherlands is commonly known within The Netherlands as "Rijkswaterstaat", often abbreviated to "RWS", and is referred to as such within this research. RWS is the operational branch of the Ministry of Infrastructure and the Environment in The Netherlands. It functions more and more as an agency in which, although RWS retains responsibility, the actual management and maintenance of assets is carried out under contract by a consortium of engineering companies, construction companies, banks, etc. The cases have been anonymized at the request of the participating parties. Two case studies were chosen. The first was that of monitoring activities of a large civil structure, in this case a bridge. The second case was the monitoring activities of a section of highway in The Netherlands. The case studies were explorative in method and descriptive in nature. Unstructured interviews were held with managers, subject matter experts, and internal consultants. Internal documentation concerned with the use and implementation of new data sources was studied. The expectations and current use of IoT data sources found in the case studies were listed. Uses and expectations were then grouped according to concept and compared with the evidence from the literature review.

3 LITERATURE REVIEW

Public infrastructure systems consist of many different types of assets that could have long life cycles. Civil infrastructure assets need to be maintained to ensure their optimal value over their entire (long) life cycles (Hassanain, Froese and Vanier, 2003). We follow Mohseni's (2003) definition of AM as being a discipline for optimizing and applying strategies related to work planning decisions in order to effectively and efficiently meet the desired objective. AM helps public organizations realize value from assets whilst balancing financial, environmental and social costs, risks, quality of service and performance related to assets (ISO 55000, 2014).

As early as 2001 there were already many software tools for asset management, (Vanier, 2001; Hassanain, Froese and Vanier, 2003; Flintsch and Chen, 2004), and since then many data formats, data sources and pools of unstructured data have become available over the years. The explosive growth in data is due to a number of different enabling and driving technologies such as the widespread roll-out of fixed and mobile internet; the development of ubiquitous computing and the ability to access networks and computation in many environments (Kitchin, 2014).

It is expected that IoT will be used in a variety of ways related both to the real-time measurement and analyses of data as to trend analysis of historical data over time (Brous and Janssen, 2015b). The variety of using IoT enables further understanding of the conditions and factors for effective and sustainable adoption of new data sources. Following from that, we focus on the review of theoretical discussions in the relevant articles on the varied ways in which IoT is used.

In information technology (IT) research, an accepted and suitable way to review literature is through the distinction of three levels: strategic/political, tactical and operational (Ackoff, 1971; Ivanov, 2010). This distinction is also recognized in asset management literature via asset owner, asset manager and service provider (Woodhouse, 1997; Volker *et al*. 2012; CROW, 2017).

In correspondence to this distinction, Table 1 summarizes the expected strategic, tactical and operational uses of IoT found in literature. The review reveals three expectations of IoT data. First, the literature expects that it will change performance measurement of infrastructure services, like applying statistical learning (Archetti, Giordani and Candelieri, 2015). Second, IoT data is expected to change the perception of infrastructure services, like perceiving sudden changes in temperature by which a fire could be detected (Hentschel *et al.*, 2016). Finally, IoT data is expected to change improvement processes, for example through self-organizing resource planning. In the next sections, we describe these uses of IoT.

Table 1. Overview of expected uses of IoT data found in literature

	IoT data expected to change performance measurement of infrastructure service	**IoT data expected to change perception of infrastructure service**	**IoT data expected to change improvement processes of infrastructure service**
Strategic use of IoT data	• Decision support services (trend analysis) (Aono *et al.* 2015) • Reporting (Backman and Helaakoski, 2016; Kothari *et al.* 2015)	• Communication of long term planning and strategic choices • Improve perceived optimization of services (Sadeghi, Wachsmann and Waidner, 2015)	• Encourage proactive processes (Aono *et al.* 2016) • Encourage self-organization (Sadeghi, Wachsmann and Waidner, 2015) • Determine strategic changes to infrastructure
Tactical use of IoT data	• Cost management (Archetti, Giordani and Candelieri, 2015 ; Aono *et al.* 2016) • Time management (Aono *et al.* 2016) • Planning (Archetti, Giordani and Candelieri, 2015) • Post-events evaluations (Tao *et al.* 2014; Hashi *et al.* 2015)	• Communication of short term planning and actions (Archetti, Giordani and Candelieri, 2015) • Improve perceived quality of services (Archetti, Giordani and Candelieri, 2015) • Public enactment (Tien *et al.*, 2016)	• Enable directed procedures (Aono *et al.* 2016) • Enable efficient recovery (Tien *et al.* 2016) • Control event occurrence (Tao *et al.* 2014; Parkinson and Bamford, 2016) • Improve utilization of existing infrastructure (Koo, Piratla and Matthews, 2015; Hentschel *et al.* 2016)
Operational use of IoT data	• Improve efficiency of monitoring (Ahlborn *et al.* 2010) • Improve quality of monitoring (Phares *et al.*, 2004; Hentschel et al. 2016) • Improve operational decision-making (Neisse *et al.*, 2016) • Improve productivity (Hentschel *et al.*, 2016)	• Communication of operational activities (Hentschel *et al.*, 2016) • Improve perceived quality of delivery (Ahlborn *et al.* 2010)	• Improve efficiency of operations (Zhang *et al.*, 2015) • Improve effectiveness of operations (Neisse *et al.*, 2016)

3.1 Expected Strategic Uses of IoT Data

Decision support services include support for management at the tactical and strategic levels. IoT services are knowledge intensive and require collection of appropriate data contents, data analysis and reporting (Backman and Helaakoski, 2016). As such, statistical learning and network science is expected to play a critical role in converting data resources into actionable knowledge (Archetti, Giordani and Candelieri, 2015).

Due to increasing stresses on budgets and personnel as well as increased utilization of civil infrastructure, public AM organizations increasingly need to intelligently manage their infrastructure with fewer resources (Rathore *et al.*, 2016). By managing and analyzing various IoT data, it should be possible to create new services to achieve an efficient and sustainable civil infrastructure (Hashi *et al.*, 2015; Backman and Helaakoski, 2016). IoT may bring an improved understanding of complex processes which is expected to help improve the efficiency of transport management and infrastructure services, and help with effective reporting (Kothari *et al.*, 2015).

Rathore *et al.* (2016) believe that smart management of traffic systems with the provision of real-time information to the citizen based on the current traffic situation should enhance the management performance of public AM organizations. Furthermore, improved granularity of trend analysis resulting from IoT data may help public AM organizations in being proactive with maintenance, reducing the chances of catastrophic failure (Aono *et al.*, 2016).

IoT may also be used to improve service optimization through self-organization (Sadeghi, Wachsmann and Waidner, 2015). Self-organizing systems that optimize themselves with regard to resource availability and consumption may enable optimization according to usage and de-centralized long-term support (Sadeghi, Wachsmann and Waidner, 2015).

3.2 Expected Tactical Uses of IoT Data

IoT infrastructure could potentially be used to reduce costs in terms of time and money (Aono *et al.*, 2016), as traditional methods of inspecting infrastructure, such as highway structures and bridges, for damage are often reactive in nature and require significant amounts of time and use of costly equipment. Aono *et al.* (2016) suggest that an infrastructure monitoring network could be used to quickly assess damage to infrastructure so that maintenance procedures could be directed to areas that need immediate attention. In this way, IoT may play a significant role in the channeling and transmission of data through efficient use of technology (Sakhardande, Hanagal and Kulkarni, 2016).

IoT is expected to be able to provide users with information on costs, time, environmental impact and perceived quality of services (Archetti, Giordani and Candelieri, 2015). When IoT data becomes available regarding a particular hazard, there may be opportunities to control hazard occurrence and recover using these data sources (Tao *et al.*, 2014; Parkinson and Bamford, 2016) and trigger analysis with events that affect measurement, such as repair or maintenance (Koo, Piratla and Matthews, 2015; Hentschel *et al.*, 2016). By specifying events (Tao *et al.*, 2014; Hashi *et al.*, 2015), it should be possible to obtain a set of data before and after an event to be used for analysis and evaluations, taking the effect of the event into consideration.

It is also expected that IoT will improve the utilization of existing infrastructure (Koo, Piratla and Matthews, 2015; Hentschel *et al.*, 2016). For example, Koo *et al.* (2015) suggest that an automated system condition monitoring based on IoT including leak detection can optimizing water supply, production, and water consumption (Koo, Piratla and Matthews, 2015).

IoT may enable more effective and efficient AM planning according to variations in user preferences (Archetti, Giordani and Candelieri, 2015) by providing decision support functionalities which identify and address criticalities in civil infrastructure. Archetti *et al.* (2015) give the example that commuters may use socially aware and collective intelligence based on functionalities of IoT to make individually informed mobility decisions. But for this to be realized, the collected data must have significance for operations and services such as inventory, usage, environmental management, and events. Also, quality of the information must be considered with regards to multiple aspects and dimensions. IoT data should be "fit-for-use" (Backman and Helaakoski, 2016; Cao *et al.*, 2016). For example, closures of bridges that are part of major transportation arteries tend to be major events. These events often result in "tweets" that point to the same incident (Tien *et al.*, 2016), which if analyzed correctly may improve service efficiency and enable more effective recovery.

3.3 Expected Operational Uses of IoT Data

In order to keep civil infrastructure such as bridges safe and functioning, regular inspections to determine the condition of the asset are a necessity (Ahlborn *et al.*, 2010; Neisse *et al.*, 2016). For example, traditional inspections of bridges are usually visual assessments by trained personnel where all the asset's component conditions are observed once every three to six years, and are summarized into one report (Phares *et al.*, 2004). After the inspection is done, asset managers must decide what maintenance interventions are needed based on these inspection reports. However, as is shown by Kallen and van Noortwijk (2005), inspection reports of bridges can be biased by subjective judgements of the experts or by lack of information. This can eventually result in inaccurate statements which may lead to the failure to perform maintenance or unnecessary maintenance activities (Phares *et al.*, 2004).

IoT data may make it possible to remotely observe the condition of objects and thereby enhance the available information on the condition of public infrastructure (Ahlborn *et al.*, 2010). IoT data is expected to allow users to monitor current environmental conditions affecting the asset. Event processing should be able to support individual, complex events if these events are defined by individual users for localized events (Hentschel *et al.*, 2016). Examples given by Hentschel *et al.* (2016) are sudden increases in sound, light and temperature, which could indicate a fire or an explosion. Hentschel *et al.* (2016) expect that when an event is triggered alarms could be issued.

Environmental factors such as temperature and air quality can have significant effects on productivity (Hentschel *et al.*, 2016). Smart assets may be able to monitor status parameters, analyze this data and reach some conclusions, considering at the same time tensions such as cost and efficiency with regards to environment preservation (Moreno *et al.*, 2014). As such, IoT data is also expected to play a role in increasing public safety and security (Neisse *et al.*,

2016) through, for example, active road safety, emergency vehicle warning or collision risk warning.

IoT data is expected to be leveraged for increased efficiency in various public service applications such as inspection schedules, public facility management, urban infrastructure maintenance, intelligent transportation services, and emergency situation monitoring (Zhang *et al.*, 2015). By enabling individuals and organizations to share real time data, IoT may enable appropriate data services to the consumers (Kothari *et al.*, 2015). The expectation is that IoT will be used for key decision making in operational activities.

4 CASE STUDIES

Two cases have been studied to identify how the adoption of IoT data is done by asset management organizations. The case studies focus on the AM process of civil infrastructure in The Netherlands. In the first case we study the adoption of IoT data by a consortium for the maintenance of a bridge. In the second case we study the adoption of IoT data for the maintenance of the road sections of a highway between two cities in the east of The Netherlands.

4.1 Case 1: Bridge Inspection with a Drone

IoT is expected to enable remote sensing of the condition of bridges and enhance the available information on their condition if performed correctly (Ahlborn *et al.*, 2010). Since limited examples of IoT adoption for bridge maintenance were known, a consortium of interested asset management organizations started a pilot to adopt remote sensing techniques to assess the condition of a bridge and its need for maintenance.

For this bridge, new methods of remote sensing have been tested, in the expectation to pilot with IoT sensors in the succeeding year to improve the quality of monitoring. For this case, the main driver for IoT and other forms of remote sensing appeared to be the lack of accessibility of some parts of the bridge for visual inspections. For example, locations above and below the bridge there is no space for setting up equipment (e.g. scaffoldings, boom lifters or ladders) such that visual inspector can work. This way, parts of the bridge remain poorly inspected, making it harder to physically detect local cases of bridge deterioration.

In combination with the innovation program of RWS, the maintenance consortium used the pilot project to perform inspections with help of a drone that was equipped with a camera to observe the less reachable parts of the bridge, thereby increasing the operation's efficiency. The drone inspection was also performed at better reachable parts to compare the inspection results of the drone against the inspection results of a human inspector. This comparison gave new data for the usefulness of adopting IoT data, since the use of drones during inspection was relatively new for bridge assessments.

In terms of a strategic use of IoT data, the consortium judged that the obtained information was good enough to give a reliable overview of the found damages at the bridge parts, which were harder to reach. This shows that the decision support services and performance report could be based on a more complete view of bridge data.

In terms of a tactical use of IoT data the consortium found that the bridge inspection with the drone resulted in less costs than a human inspection with the needed equipment to access the areas of the bridge. Therefore, the adoption of drones results in a reduction of costs with respect to inspecting a bridge.

On the operational use of IoT data, the adoption of a drone showed practical constraints. The drone did not receive a GPS signal under the bridge deck which prohibited it to follow its predetermined flight route. Therefore, it had to be steered manually which made the process of documenting and keeping record of the locations of the taken inspection photographs more difficult and time consuming than expected. Secondly, the damages themselves were clearly visible but the extent and size were hard to measure from only the digital images. Thirdly, the drone had to fly at a minimum distance of 1.5 meters from the bridge components which resulted in the incapability of observing the bearings of the bridge and affected the completeness of the drone's dataset. Finally, the bridge had to be closed off for traffic due to safety regulations.

The consortium concluded that the use of drones is not ideal for assessing bridges. This conclusion could be overturned when the practical downsides of the drone flight are solved. Nevertheless, the interviewed asset managers still expect that remote sensing will eventually be able to compare the actual behaviour of the bridge components with the expected behaviour at much shorter intervals, giving asset managers a better opportunity to construct a more qualitative, efficient and effective maintenance plan.

Another interesting side-note with regards to this case of adopting drones for bridge inspections, is that the consortium has made further plans to implement a pilot project using IoT sensors that communicate over a Long-Range Low-Power (LoRa) network to monitor bridge movements. Robust, smart wireless sensing systems that are suitable for use in civil engineering have been developed specially for this project, as well as the software to analyse and interpret the data. According to the interviewees, these new sensing methods should speed up and improve current monitoring methods.

4.2 Case 2: Highway Connection Between Two Dutch Cities

An asset management organization under contract in the East of the Netherlands had the task to increase the safety of a highway between two Dutch cities. In addition, the organization had to improve the connection to surrounding villages. The highway in the contract stretches for 23 km. The asset management organization worked under a new maintenance contract adopted by RWS, but this contract included no requirements for adopting IoT data. It is worth noting that this type of contract was representative for other maintenance contracts in The Netherlands at the time.

Traditional inspection methods were performed through annual measurements with an Automatic Road ANalyser (ARAN) vehicle and visual inspections. These were the only inspection methods that RWS, the contracting authority, accepted. Since the data on performance or its perception could not be changed with IoT data, the added value could only come from improving the main inspection method.

Therefore, to be better able to inspect the road the asset management organization adopted various additional IoT-based techniques. For example, the organization chose to use cloud-based service lane technology to monitor the road. They adopted these techniques with the intent to enable their inspectors to add inspections quickly while on location and to help asset managers to see the information with a better overview. This case shows that adoption of IoT data to change the operational efficiency was possible, despite the contractual requirement.

Still, for the tactical use of IoT data some limitations remained. The asset management organization could not yet adopt IoT data with respect to making the assessments. This still had to be done by experts judging the extent to which the deterioration as inspected and monitored should be resolved with control measures. As this was still mostly a manual process these experts defined control measures while trying to combine the deterioration overviews of ARAN and the IoT techniques, and by coupling various road sections to judge the quality between these. Experts were still needed because non-condition data had to be included for determining the appropriate action, eg. scheduled maintenance tasks, the cost of repairs and cost of a penalties.

At a strategic level, the adoption of IoT data started to show a conflict of interest between the asset management organization and the contracting authority. When a failed requirement was detected, the contractor was obliged to inform the contracting authority and notify them of the intended actions. The contractor ensured there was proof of Quality of Service, while, at the same time, the contracting authority also inspected the same section of the road to check if the used measurements were correct. The conflict of interest typically surfaced in this case at the point where assurances were needed to meet requirements in the contract. On the one hand, requirements helped the contracting authority manage the contract, by use of financial compensations and penalties. On the other hand, the contractor took the view that requirements could be handled more flexibly if they were managed independently. This conflict showed that an asset management organization under contract did not choose to adopt IoT technologies because of the persistence of the contracting authority to use established methods, thereby missing the expected benefits of more self-organized and more proactive highway inspection.

5 DISCUSSION

Civil infrastructures such as transport infrastructure systems present unique opportunities for developing new applications aligned with IoT and it is expected that IoT will play a significant role in AM processes in the future. Civil infrastructure systems provide many of the services that are critical to the continued functioning, and security of society (Tien *et al.*, 2016) and failure of these infrastructures can be catastrophic. Detecting these damage or failure events is critical to minimize the negative impacts of these events, but many of these infrastructures still lack continuous monitoring to be able to detect these events (Tien *et al.*, 2016). Bridges, for example, are generally subject to only three to five yearly inspections, and very few are instrumented with physical sensors that would be able to detect damage that may occur at any time. The opportunities for IoT adoption are apparent, and expectations appear to be high. However, adoption of IoT remains low. Noticeably, current data sources are still largely provided by expert judgement in combination with technical devices in specific measurement points, although a growing role is being played by human data generated through, for example, social networks (Archetti, Giordani and Candelieri, 2015). Table 2 below outlines the conditions and factors found in the cases and literature, grouped according to elements of data infrastructures as suggested by Brous *et al.* (2014).

Table 2: Conditions and factors for IoT adoption in AM.

Category	Conditions and Factors
Human	High technical knowledge Good understanding of data management processes Good understanding of data quality issues Ongoing training and education
Organizational	Clear responsibility for innovation Availability of best practices to benchmark Positive business cases. Data Governance: Clear responsibilities for data management
Data	Data Governance: High level of data quality Alignment of data to AM requirements
Technical	Data Governance: Adoption of stringent security measures Availability and adoption of interoperability standards

Adoption of IoT in AM is facing challenges to integrate data from diverse data sources and to design applications to support the management of infrastructures (Brous and Janssen, 2015a). Statistical learning is thus expected to play a critical role in the design of representation models and computational engines needed to turn the data resources into actionable knowledge (Archetti, Giordani and Candelieri, 2015).

According to Aono *et al.* (2016), IoT is only practical if the IoT infrastructure matches the useful life of the physical asset. But Kothari *et al.* (2015) believe that there is still some work required on building IT infrastructures for supporting the IoT ecosystem. IoT infrastructures require powerful mechanisms for sensor feed discovery, planning of feed processing workflow, failure resilience and system management (Kothari *et al.*, 2015). As seen in the cases, existing IT infrastructures often do not yet provide these capabilities, thus requiring high-levels of manual intervention (Kothari *et al.*, 2015). Furthermore, although quality of sensor feeds is critically important, little attention is currently paid to data quality in most existing infrastructures (Kothari *et al.*, 2015).

The importance of data quality for IoT infrastructures and the persisting requirement for manual intervention suggests the need for instituting strong data governance procedures as data quality issues are often do not arise from existing business rules or the technology itself, but from a lack of sound data governance (Thompson, Ravindran and Nicosia, 2015) and data quality is often seen as an important metric for data governance (Brous, Janssen and Vilminko-Heikkinen, 2016). Data governance is the exercise of authority, control, and shared decision making over the management of data assets. It provides organizations with the ability to ensure that data and information are managed appropriately, aligns the data infrastructures with business requirements, ensures a common understanding of the data, and ensures compliancy to laws and regulations (Brous, Janssen and Vilminko-Heikkinen, 2016).

Aligning complex data structures such as semantics or ontology between different IoT eco-systems is a complex task and interoperability and convergence with regards to visibility of processed data at the level of applications remains an issue (Mihailovic, 2016). This barrier has hampered IoT data sharing. According to Cao *et al.* (2016), sharing of IoT data will only reach its full potential if data can be collected by multiple sources such as if people are able to share their data related to different events by leveraging the sensing capabilities of their smartphones (Cao *et al.*, 2016). But some of the data collected by smartphones may contain sensitive information such as the location data of the owners. Compliancy to privacy and security regulations is imperative. In Europe, the new General Data Protection Regulation (GDPR) defines the conditions under which personal data can be processed, specifying that consent must be unambiguous. To provide informed consent regarding the use of personal data, the citizen must have a clear understanding on how his/her personal data will be used by the ICT systems and applications and especially in the emerging paradigm of IoT (Neisse *et al.*, 2016).

In addition to the resolution of data quality issues, data governance may also assist IoT adoption in other ways as data governance provides both direct and indirect benefits (Ladley, 2012). Direct benefits of data governance for business processes can be linked to efficiency improvements (Hripcsak *et al.*, 2014), reductions in privacy violations (Tallon, 2013), and increased data security (Panian, 2010). Indirectly, data governance also improves the perception of how information initiatives perform (Griffin, 2010), improves the acceptance of spending on information management projects (Thompson, Ravindran and

Nicosia, 2015), and improves trust in information products (Otto and Weber, 2011).

6 CONCLUSIONS

Currently, organisations are experimenting with new data sources and there is a general expectation that IoT will provide significant added value to AM decision making. Organisations can effectively and sustainably adopt these new data sources in their AM decision making if the data that is measured can monitor the important factors of the asset itself. Adoption of IoT requires an IT infrastructure that can facilitate the new data sources and requires a good understanding of the data collected and its quality aspects. Adoption of IoT needs appropriate management of the data to ensure compliancy to laws and regulations. Sound data governance is required to ensure that IoT can provide trusted data for AM decision making.

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