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# Workspace optimization in Smart Buildings:

## Design of an Interoperable IoT Architecture

Deloitte.

TU Delft

# Workspace Optimization in Smart Buildings:

## Design of an Interoperable IoT Architecture

By

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# Foreword and Acknowledgements

In front of you is the final version of my thesis, the result of several months of hard work. As this is the second thesis I have written, I was already familiar with the infamous 'thesis-stress' that inevitably overcomes everyone at some point during this process. My familiarity with the pitfalls of conducting research allowed me to make a planning that was tight, but still flexible. For example, by selecting interview respondents and planning the interviews several weeks in advance, while anticipating cancellations, ensured that I was able to collect enough data, even though several interviews were cancelled at the moment they were due. A clear plan allowed me to perform multiple tasks at the same time, in parallel, resulting in a more efficient research process. In essence, I was able to *optimize* the process.

Optimization is what this study is about; the optimization of workspaces. I assess how workspace in buildings can be used more efficiently, based on data that is collected by sensors that are placed throughout the building.

I would like to thank several people that have supported me during my studies and graduation. First of all, my graduation committee. Thank you, André, for being my first supervisor and guiding throughout the process with lots of tips. Thank you, Farzam, for the numerous calls we've had and all the good ideas that you came up with. Thank you, Martijn, for steering me where needed and providing me with directions. At last, thank you Yao-Hua for being the chair and ensuring the quality of my research.

Further, I would like to thank Deloitte Consultancy, and in particular Mohammad Khelghati, for providing me the opportunity to write this thesis in combination with an internship. Thank you for your great insights and ideas on this topic, as well as access to the building for the case study. I have learnt a lot in these months; I know my strengths and weaknesses much better.

At last, I would like to thank my family and friends for their support during this process. In particular my parents, for providing me with the opportunity to pursuit this study in Delft, as well as the best care and support one can ask for. Last but not least, my supportive girlfriend for her endless patience and guidance during this process.

Yours sincerely,

Vishan Baldew

# Summary

The main topic of this thesis, *workspace optimization,* is introduced by describing how office buildings have changed over time and the challenges that arise from this. Traditionally, when you worked for a big company, you would be working in a big office with all your colleagues. Everyone would arrive at around 08.30 and sit at their own desk or own office. If you needed a colleague, you could just walk to their (designated) desk. At the end of the day, at 17.00, everyone would leave the office again. Fast forward to more recent years and the working landscape has shifted. Due to improvements in digital technologies, people are able to work more and more from other places than their company's office; working from home or at the client's office is increasingly common, and in some companies even stimulated. In particular professional workers, such as consultants, are visiting their company's office less frequently or at irregular times.

To cope with this dynamic and unpredictable occupation, office layouts have changed – fixed desks and working offices have made place for large open floor plans with non-designated desks. The number of workspaces in relation of the workforce has also been reduced significantly, as only a portion of the employees is expected to come to the office. Even though this allows for a more efficient use of the office, several challenges are raised. First of all, as there are no designated desks, you need to find a workspace that suits your preferences, such as being in a quiet area or nearby your colleagues, every time you arrive at the office. Especially on busy days, this can be difficult. Next to that, you cannot easily walk towards the desk of your colleague if you need him/her, as they don't have a fixed desk.

For that reason, *workspace optimization* is introduced to handle these challenges. By equipping the building with sensors, i.e. *Internet of Things (IoT)* devices, that collect all kinds of data, the 'smart' building is able to help you decide where you need to sit. Suitable workspaces that fit your preferences can be suggested when you enter the building. Further, the location of your colleague in the building, can be requested, which is easier than calling or searching them in the office.

Equipping buildings, or even cities, with sensors to make them 'smarter' is a trend that has been ongoing for several years. Despite of this, there are still several questions that need to be answered before such a solution can be deployed. Questions such as: *'How can you measure which desks are vacant?'* and *'How can you know where a colleague is sitting?'* But also questions related to IoT systems in general, such as: *'What are best practices for the design of IoT systems?'* and *'What kind of data needs to be collected and how does this data need to be managed to provide suitable suggestions?'*

In current literature on workspace optimization is found that several studies exist that asses techniques for measuring building occupancy. However, these studies cannot directly be used by organizations to design a workspace optimization solution, as these studies are mostly performed in small-scale test settings, don't measure occupancy to the desk-level, and don't describe what kind of data needs to be collected and how this data needs to be handled to provide relevant suggestions. In other words: a structured design/architecture that can be used by organizations to design and implement such an IoT solution is currently missing.

In total, four knowledge gaps have been found in literature on *workspace optimization*, *smart cities and smart buildings*, and *IoT architectures*:

1. There is a lack of academic research on workspace optimization, a structured design / architecture that can be used to design and implement such a solution is missing
2. Due to differences in approach of IoT use cases, there is the threat that the IoT devices and solutions remain isolated and cannot communicate with each other effectively, reducing potential for smart cities and smart buildings
3. There is a need for common understanding between stakeholders that are involved in use cases for smart cities and smart buildings

4. A clear focus on capabilities for data management is lacking in IoT solutions, whereas this needs to be taken into account from the start, especially when privacy sensitive data is collected.

Based on these knowledge gaps, the following research objective has been stated: to design an IoT Architecture for workspace optimization in smart buildings that is based on common guidelines, scalable, involves relevant stakeholders, and integrates capabilities for data management in the design.

To fulfill this objective, a *design science* approach is used to design an IoT architecture for workspace optimization in smart buildings through empirical research. First, a desk study is performed to select a suitable IoT reference architecture to guide the design process, to collect an initial set of requirements from literature, and to identify relevant stakeholders to involve in the design process. After that, these stakeholders are interviewed to collect additional requirements for the workspace optimization solution, as well as to prioritize them. Interviews are conducted with *employees, facility managers, data scientists, information systems managers,* and *privacy officers*. In total 46 requirements have been collected, of which 26 are rated as high priority. After an initial architecture design, interviews with four experts are conducted to evaluate the architecture; two IoT architects, one data scientist, and one IT expert.

Based on the collected requirements and expert evaluation, four architectural views are (re)designed for the workspace optimization solution:

- Context View: sets the system scope and provide a clear visualization of important parts of the system
- Functional View: provides a detailed description of functions in the system, grouped in functional components and functional groups
- Information View: provides an overview of relations between important users, hardware and software in the system, as well as the information flow
- Physical-Entity View: provides a detailed description physical entities, their digitally represented virtual entities, and important IoT devices

Next to that, two process views are designed that provide a better understanding of (1) how the system is used by users, and (2) how the four architectural views can be used to derive a specific *solution architecture* for the implementation of such a system in practice.

Highlights of the systems are the following: three data sources are used to collect data: *MotionSensors* to measure meeting room occupancy, *DeskSensors* to measure desk occupancy, and *AP-Sensors* to indicate the location of employees in the office (WiFi triangulation is used to find the location of their laptop, which is used as a proxy of the employee location). Further, to preserve the employees' privacy, their location is only tracked after an explicit opt-in, this is needed to comply with law and regulations regarding personal data collection. Next to that, a Data Lake is used to integrate and store all data that is collected (except for employee-location data, which is stored in a separate data base and flushed after the predictive model has been updated). Using a data lake was found to be useful for future use cases, as traditional data integration and storage systems (e.g. a data warehouse) don't store data that isn't needed directly, which might result in a loss of potentially valuable data.

Important scientific contributions of this study are that

1. A workspace optimization architecture is created, as well as requirements for such a solution are collected that can be used to support the design and implementation of such a solution – this is found to be lacking in current literature.
2. An extension is proposed to the reference architecture that is used in this study (IoT-A) – an integration of data management is found to be lacking in current architecture, even though this is stated to be important by researchers.

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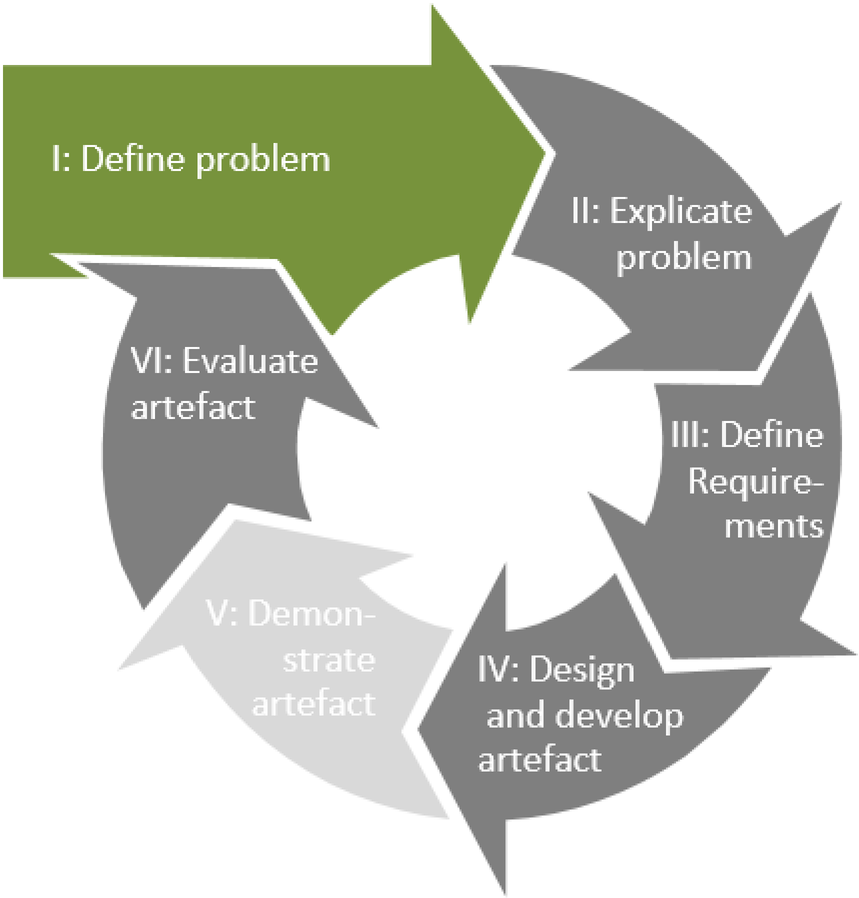
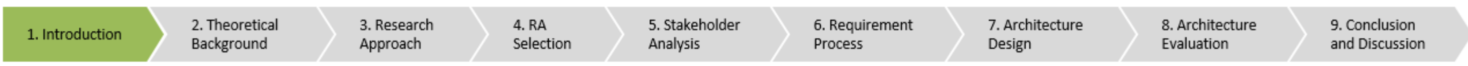
# List of Definitions

| **Term** | **Definition** |
|---|---|
| Architectural view | *"A representation of a whole system from the perspective of a related set of concerns"* (IEEE-SA, 2000) |
| Architecture | *"The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution."* (IEEE-SA, 2000:3) |
| Artefact | *"an object made by humans with the intention that it be used to address a practical problem"* (Johannesson & Perjons, 2014:3) |
| Data Analytics | *"actions and methods performed on data that help describe facts, detect patterns, develop explanations, and test hypotheses" (U.S. Geological Survey, 2015)* |
| Data Integration | *"the process of combing data residing at different sources, and providing the user with a unified view of these data" (Lenzerini, 2002:233)* |
| Data Processing | *"Any set of structured activities resulting in the alteration or integration of data" (U.S. Geological Survey, 2015).* |
| Data Storage | *"actions and procedures to keep data for some period of time and/or to set data aside for future use, and includes data archiving and/or data submission to a data repository" (U.S. Geological Survey, 2015)* |
| IoT-A | *Internet of Things Architectural Reference Model, developed in the 'Internet of Things Architecture European Project'* (Carrez et al., 2013) |
| IoT | *Internet of Things* |
| Stakeholder | *"A person, group, or entity with an interest in or concerns about the realization of the architecture"* (Rozanski & Woods, 2011:1) |
| Stakeholder concern | *"A concern about an architecture is a requirement, an objective, an intention, or an aspiration a stakeholder has for that architecture"* (Rozanski & Woods, 2011:1). |
| UNIs | *Unified requirements* (Carrez et al., 2013) |
| Workspace Optimization | *Measuring, monitoring and predicting building occupancy through IoT devices, and using this information to optimize workspaces* |

# Phase I: Define Problem




This is the first phase of *Design Science Framework* by Johannesson & Perjons (2014). In this phase, the problem on which this thesis focuses is introduced and briefly explained. Chapter 1: Introduction is part of this phase.



# 1. Introduction

This chapter will introduce the thesis topic by briefly describing the current situation of the research fields, the knowledge gaps, and the resulting research questions. The scientific and practical contribution of this thesis will be described, and this chapter ends with the outline of the thesis.

## 1.1.Research Problem

### *1.1.1.Problem exploration*

In recent years, the traditional work environment is evolving, resulting in a need for more flexibility in the use of office space. 'New ways of working' is a paradigm that is increasingly used by researchers to describe changes in the traditional work environment, where workers are not fixed to a particular location, but work from home or their client's office (Spinuzzi, 2007), This becomes possible by e.g. improvements in mobile technologies (Faraj & Azad, 2012). Especially workers that are paid for their professional efforts, such as consultants, are increasingly less fixed to a particular location to perform their work (I. Erickson & Jarrahi, 2016).

These changes in the working landscape have led to several initiatives to cope with the dynamics of office occupation: hot-desking; where employees have no fixed desk but work from any that is vacant, and open floor plans; large areas with no physical boundaries between workspaces (Millward, Haslam, & Postmes, 2007). Benefits of these initiatives are e.g. costs savings, through a more effective use of office space, and more fluid networking between employees (Hirst, 2011; Millward et al., 2007). Though recent research suggests that there are also disadvantages of hot-desking and open floor plans, e.g. more distraction that decreases employees' ability to perform deep work in open spaces (Newport, 2016), a decrease in team identity identification with no assigned desks (Millward et al., 2007) and difficulties to finding and meeting colleagues (Biggart et al., 2016; Slawson, 2016; UVA, 2014). Thus, finding a fine balance and delivering an optimal working environment that adapts to the dynamics of the assignments of the employees in the changing working landscape is subject to numerous constraints.

*Workspace optimization* is therefore gaining attention of both academia and businesses, because this makes it possible to track occupants in buildings and use this data to optimize utilities or even predict future occupation. In journal articles and whitepapers the following benefits are mentioned: (1) it provides an understanding in how a building is used, which allows to make decisions for long-term capacity planning. (2) By collecting occupancy-data to the desk level, employees can find vacant desks in the building. (3) Employees can find where their colleagues are located (Serraview, 2015). (4) The energy consumption of the building can be optimized, e.g. by closing unused floors (Nguyen & Aiello, 2013; Paola, Ortolani, Re, Anastasi, & Das, 2014). (5) Emergency situations in the building and security can be handled better by getting insight in the number and precise location of employees (Hitiyise, Ntagwirumugara, Habarurema, Ingabire, & Gasore, 2016; Nyarko & Wright-Brown, 2013).

In particular two trends in recent years has enabled workspace optimization. On one hand there is the cost-reduction and exponentially improvement of sensing equipment that has opened up opportunities to place e.g. sensors and actuators in buildings, resulting in 'smarter' buildings that allow facility managers to monitor and improve resources based on the collected data (Intel, 2015; Kejriwal & Mahajan, 2016). On the other hand exponential improvements in cloud computing and machine intelligence have enhanced the analytical capabilities that are needed to analyze the (potentially) huge amounts of data that is collected over time (Y.-K. Chen, 2012; Tyagi, Darwish, & Khan, 2014). Nevertheless, workspace optimization as a research field is still in development. There are multiple studies that discuss techniques for occupancy measuring in buildings based on sensors (Balaji, Xu, Nwokafor, Gupta, & Agarwal, 2013; Melfi, Rosenblum, Nordman, & Christensen, 2011). However, these studies are mainly based on small-scale test settings and conceptual ideas. Studies that discuss resource allocation (suggestion of workspaces, finding vacant desks/rooms, track individuals) are scarce. A structured design/architecture for applying these techniques and implementing workspace optimization in buildings seems to be lacking.

The sensors and devices that are embedded in *smart buildings* are part of the *Internet of Things* (IoT) vision in which *"electronics will be embedded into everyday physical objects, making them 'smart' and letting them seamlessly integrate within the global resulting cyber-physical infrastructure"* (Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012:1497). According to GSMA the number of interconnected devices overtook the number of people in the world in 2011; and this number is expected to grow to almost 24 billion in 2020 (Gubbi, Buyya, Marusic, & Palaniswami, 2013).

In fact, embedding IoT devices in buildings is part of a broader vision in which whole cities are equipped with sensors; an increasing body of literature is describing how IoT devices are adopted in the management of public affairs in order to optimize traditional public services in cities, such as lightning, parking, traffic flows and maintenance (Kitchin, 2014; Zanella, Bui, Castellani, Vangelista, & Zorzi, 2014). These initiatives have the goal to create *smart cities* in which *"ubiquitous computing and digitally instrumented devices [are] built into the very fabric of urban environments"* (Kitchin, 2014:2). One of the barriers right now is that, especially in smart cities and smart buildings, standards are needed that are open and interoperable to increase adoption. At this moment formal methodologies for interoperability, e.g. standards and widely used reference architectures are lacking (Ahlgren, Hidell, & Ngai, 2016; Gyrard & Serrano, 2016).

Due to differences in approach of applications and use cases of IoT solutions, there is the 'threat' that IoT devices remain isolated and cannot communicate with each other effectively. This lack of interoperability results in 'networks of things' (Gubbi et al., 2013) or 'intranet of things' (Duarte & Ratti, 2016) instead of fully connected internet of things. Weyrich & Ebert (2016) argue that a lack of architecture standards is the reason for this. Even though there are several reference architectures developed to overcome these interoperability issues, current solutions are not based on these standards, which hampers the integration and cooperation of different devices (Duarte & Ratti, 2016).

Next to that, an ongoing issue with IoT is that a strong focus on capabilities for data management is needed to gain value from the collected data. *"Collecting data isn't enough for businesses investing in Internet of Things projects, […] they'll have to incorporate robust analytics"* (Burns, 2014). Currently, the focus is more on connecting as many devices as possible, whereas value will only come when organizations also put focus on their capabilities for data management (integration, storage, processing & analytics) (Noronha, Moriarty, O'Connell, & Villa, 2014; U.S. Geological Survey, 2015; Zdravkovi et al., 2016).

#### *1.1.2. Problem statement*

Based on the problem exploration, it can be concluded that there are two trends that are relevant for this study. Currently, workspace optimization in smart buildings based on IoT seems promising, but a structured approach or architecture that can be used to design and implement such a solution is missing. Meanwhile, IoT solutions are mostly not based on common grounding and architecture standards, resulting in solutions that are non-interoperable. Especially in the broad vision of smart cities, interoperability of solutions is needed to form a 'network'. Also, a more explicit focus on data management (e.g. integration, storage, processing, and analytics) is needed to get real insights from the data that is collected. This focus should be there from the start of the development of the solution.

Thus, the following problem statement is derived: *workspace optimization has potential to cope with the current dynamics in the working landscape. IoT devices in devices enable this, but an IoT architecture for the design and implementation of workspace optimization is lacking.*

#### *1.1.3. Knowledge gaps*

The following knowledge gaps are derived from the problem exploration:

1. There is a lack of academic research on workspace optimization, a structured design / architecture that can be used to design and implement such a solution is missing.
2. Due to differences in approach of IoT use cases, there is the threat that the IoT devices and solutions remain isolated and cannot communicate with each other effectively, reducing potential for smart cities and smart buildings.
3. There is a need for common understanding between stakeholders that are involved in use cases for smart cities and smart buildings.
4. A clear focus on capabilities for data management is lacking in IoT solutions, whereas this needs to be taken into account from the start, especially when privacy sensitive data is collected.

## 1.2. Research objective

Based on the problem statement and knowledge gaps, the research objective can be stated as follows. The research objective is to design an IoT Architecture for workspace optimization in smart buildings that has the following characteristics:

- The architecture is based on common guidelines and architecture standards to improve interoperability with other IoT solutions
- The architecture is scalable, external data sources can be added over time
- The architecture reflects the concerns of the various stakeholders that are involved in order to include them in the discussions
- The architecture integrates capabilities for data management in the design

## 1.3. Research questions

In order to structure the thesis report of this study, the following research question is stated:

What are the design specifications of an interoperable IoT architecture for workspace optimization that integrates capabilities for data management?

The following sub questions will be used to answer this research question:

1. What are the defining characteristics of interoperable IoT architectures?
2. What are the requirements for an IoT architecture for workspace optimization in smart buildings and which relevant parties need to be involved?
3. How can a focus on capabilities for data management be integrated in IoT architecture design?
4. What are evaluation criteria and how do experts evaluate the proposed IoT architecture for workspace optimization in smart buildings?

## 1.4. Contribution

The nature of research problem and research objective indicates that this research project can be typified as a practice-oriented study, with a design-oriented research objective (Verschuren & Doorewaard, 2010). Reason for this is that the objective is to *design* an IoT architecture for workspace optimization in smart buildings. Johannesson & Perjons (2014) thoroughly describe design-oriented studies in their book *Introduction to Design Science*. They describe how a research project needs to be designed when the development of an artefact is desired or needed. They define an artefact as *"an object made by humans with the intention that it be used to address a practical problem"* (p. 3). Thus, in this study the IoT Architecture is the artefact. The authors describe how design science has the purpose to be generalizable and contribute to knowledge for a *global practice*, instead of only being relevant for a single actor. Therefore, they argue design science studies need to comply with three requirements:

1. Rigorous research methods need to be used to create knowledge of general interest.
2. The knowledge that is produced needs to be related to a scientific body of knowledge, to ensure that the findings are both well-founded and original.
3. New results need to be communicated with both practitioners and researchers.

Johannesson & Perjons (2014) describe the relationship between a design science project and the *global practice* with the visualization in Figure 1 that is an adaption of the work of Goldkuhl (2012).

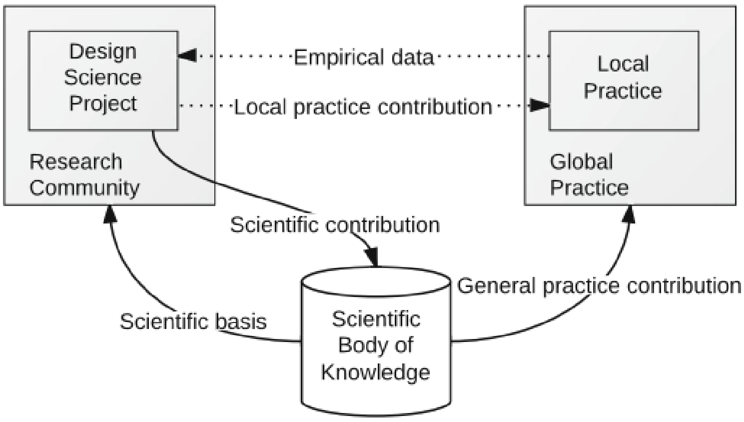



*Figure 1 – Design science research (Johannesson & Perjons, 2014)*

Therefore, this study has both scientific and practical relevance, these will be described in the following sections.

### *1.4.1. Scientific relevance*

The scientific contribution of this study is as follows: first of all, the research field of *workspace optimization* is relatively nascent, as existing studies are mostly focused on small-scale test settings for occupancy measuring techniques in buildings. An architecture for the design and implementation of a workspace optimization solution is found to be lacking. Further, current literature describes four high-level, conceptual requirements for such a solution: *low cost*, *non-intrusiveness*, *high accuracy*, and *privacy-preserving*. In this study, more specific requirements will be identified and prioritized. These requirements are subsequently used to design 4 architectural views, and two additional process views to support the design and implementation of such a solution.

At last, it is stated that a focus on capabilities for data management is extremely important in order to attain value from IoT systems. Currently, organizations focus more on connecting devices, and data management is dealt with in a later phase – by incorporating design choices regarding capabilities for data management already in the design-phase, IoT systems are more robust, and more value can be gained. This study proposes an extension of the reference architecture that is used that integrates a specific focus on data management. This can be used by researchers of the reference architecture to include in a future version of the reference architecture, as well as by systems designers for the design of use case-specific architectures.

### *1.4.2. Practical relevance*

Next to that, this study has also practical contributions: first, specific IoT use cases in smart buildings are needed to stimulate the development of smart cities. Researchers state that a lack of specific use cases hampers the development of smart cities, the added value of sensors and extensive data collection in e.g. buildings needs to be proven to show business value and provide the various stakeholders that are involved in smart city-projects with concrete, working examples.

Further, facility managers or real estate developers that are interested in a solution to cope with dynamic occupation in their (smart) buildings, are presented with an IoT architecture for workspace optimization that is based on a widely-used reference architecture. This architecture can be used to specify a building-specific architecture and subsequently implement a workspace optimization solution in offices to e.g. optimize the energy usage, or to make it easier for occupants to find vacant desks/rooms. Also, the common grounding on which this architecture is based improves interoperability with other use cases/applications that are based this.

At last, for Deloitte, who cooperate with this study, these findings are especially relevant. Their Amsterdam office can be seen as a smart building, *without* a solution for workplace optimization. However, this is desired, as it is challenging to find vacant desks or rooms on busy days. This architecture can be used to facilitate communication among the stakeholders that are involved in such a process, as well as serve as a guideline for the design of such a system.

## 1.5. Scope

In the Design Science framework, the following phases are described: *Explicate problem, Define requirements, Design and develop artefact, Demonstrate artefact, and Evaluate artefact* (Johannesson & Perjons, 2014). For this study, the framework will be adapted slightly: first, the phase *Define problem* is explicitly added at the start of the cycle, because this defines the starting point for the study. Further, Johannesson & Perjons (2014) visualize the phases in a waterfall model, whereas an iterative approach seems more fitting due to the complexity of the problem. At last, the phase *Demonstrate artefact* is out of scope for this study due to time constraints. See Figure 2 for a visualization of the phases as used in this study.

Regarding the scope of the research problem, the focus is on buildings that are equipped with sensors, smart buildings, in which hot-desking and open floor plans are used. By applying workspace optimization in these buildings, the building can be optimized in terms of energy usage and arrangement, whereas employees are able to find vacant desks, vacant meeting rooms, and their colleagues easier.

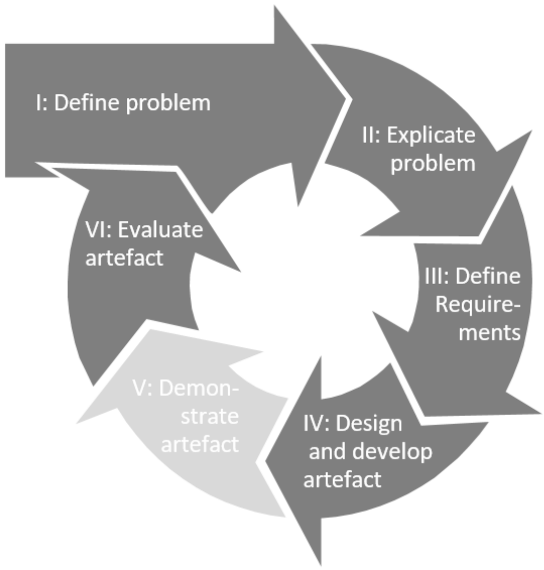



*Figure 2 –Method framework for design science research (adapted from Johannesson & Perjons (2014))*

## 1.6. Thesis outline

As described in the scope of this study, an adaptation of the method framework for design science research by Johannesson & Perjons (2014) will be used to structure this thesis. In Figure 3 is displayed how the chapters of this study are related to the phases. For illustrative purposes this is presented as a 'waterfall approach', however, the study will be performed in an iterative manner (as displayed in Figure 2).

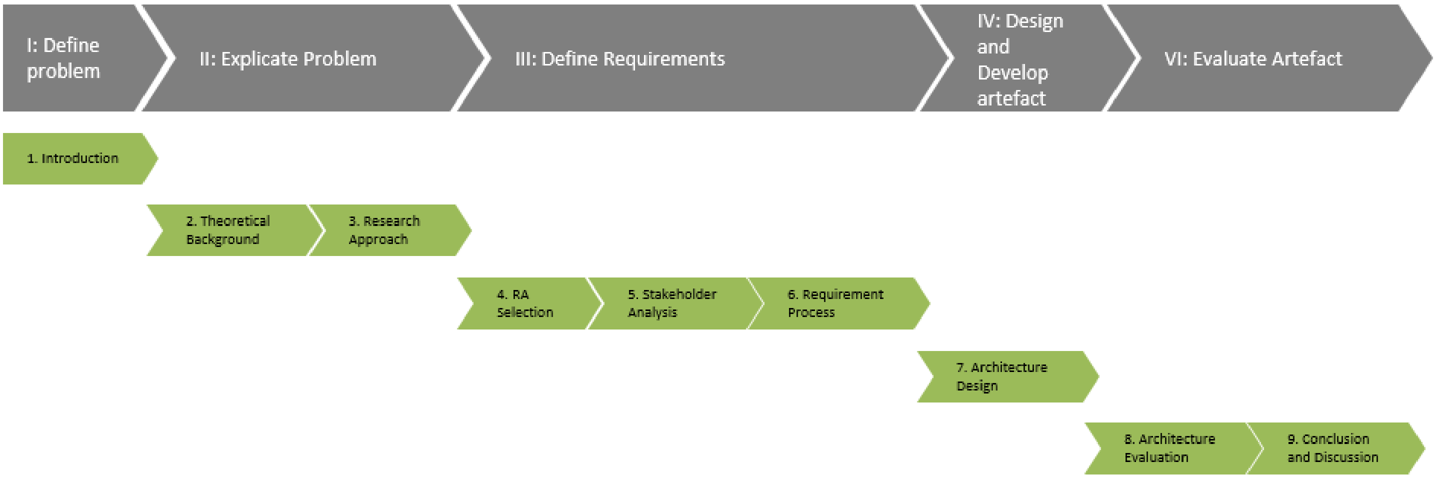
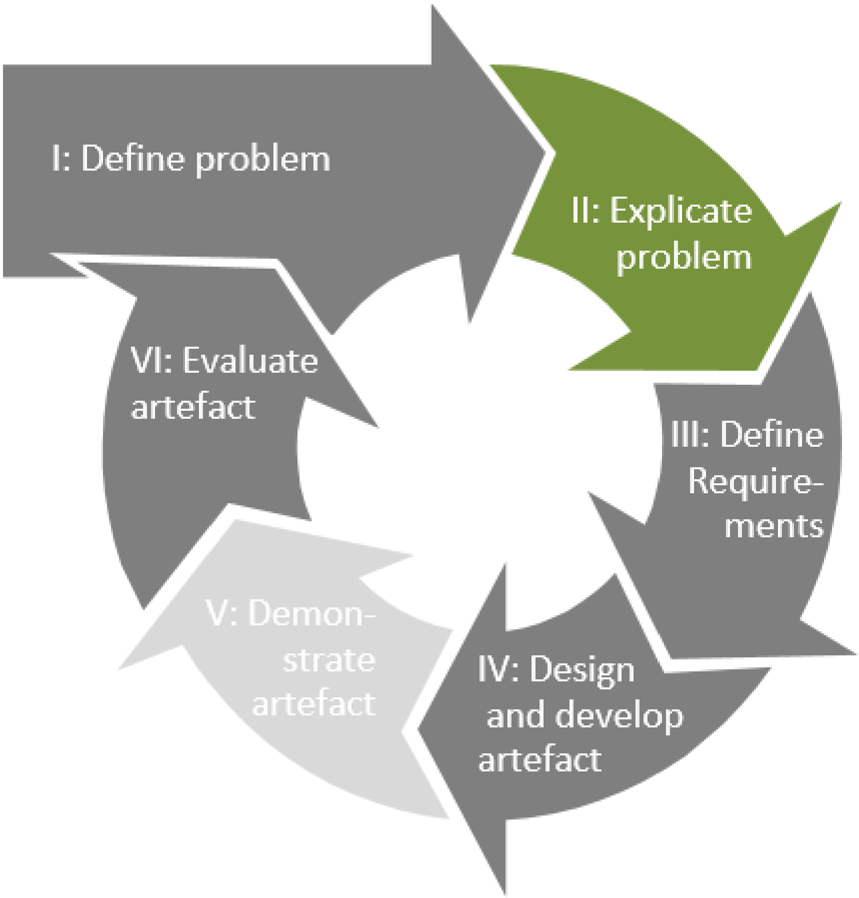
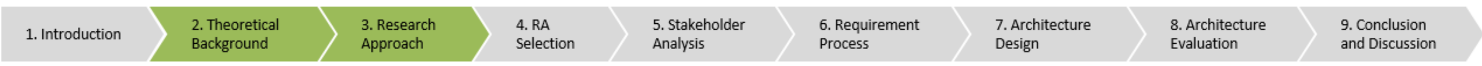



*Figure 3 – Mapping of design-phases and thesis-chapters*

# Phase II: Explicate Problem




This is the second phase of *Design Science Framework* by Johannesson & Perjons (2014). In this phase, the problem on which this thesis focuses is explored further, its importance is justified, and underlying causes are assessed. This is done through a thorough analysis of the main constructs in this study. Further, the research approach that fits the problem is explained.




Chapter 2: Theoretical background, and Chapter 3: Research Approach are part of this phase.

# 2. Theoretical Background

In this chapter, relevant research fields that are identified in chapter 1 are explicated. The following research fields will be assessed: workspace optimization, smart cities and smart buildings, and IoT Architectures.

## 2.1. Workspace optimization

In the last decade, employees have become increasingly mobile. Employees are mobile within their (large) office building, or are even able to work remotely; from their client's office or home (Spinuzzi, 2007). In particular knowledge workers are able to decouple from fixed locations and physical capital, therefore the term 'mobile workers' is often used to depict these type of employees (I. Erickson & Jarrahi, 2016). This is trend is expected to continue, the global mobile workforce is set to reach 1.75 billion in 2020; almost 40% of the total workforce according to research firm Strategy Analytics. The increase in mobile workers is encouraged by advances and improvement in technologies, such as cellular data connections, cloud computing, and online collaboration tools (Faraj & Azad, 2012). Due to this increase in mobility of employees, office occupation is becoming more dynamic and less predictable.

In order to cope with the dynamics of office occupation, companies have started with several initiatives to make better use of their office space: hot-desking and (large) open floor plans. Hot-desking is an office layout in which employees are not assigned dedicated desks, they occupy a vacant desk at the start of their workday, and clear it again at the end of their workday (Hirst, 2011; Millward et al., 2007). In open floor plans, there are no physical boundaries between workspaces, almost all office work is performed in an open space (Saari, Tissari, Valkama, & Seppänen, 2006). Benefits of these initiatives are that office space is being used more efficiently, resulting in e.g. cost savings. Also, employees are expected to have more fluid networking since they are situated in a common space that stimulates interaction (Hirst, 2011; Millward et al., 2007).

Despite these benefits, recent research suggests hot-desking and open floor plans also have certain drawbacks. Employees are distracted more easily when sitting in open floor spaces, which reduces their ability to perform *deep work* (Newport, 2016). This is especially important for knowledge workers – the group that is increasingly working mobile (I. Erickson & Jarrahi, 2016; Hardill & Green, 2003; Saari et al., 2006). Next to that, employees feel a decrease in team identity and organizational identification with no assigned desks and continuously changing people around them (Millward et al., 2007). Furthermore, there are also more practical challenges, like difficulties to finding and meeting colleagues (Biggart et al., 2016; Slawson, 2016; UVA, 2014). Thus, finding a fine balance and delivering an optimal working environment that adapts to the dynamics of the assignments of the employees in the changing working landscape is subject to numerous challenges.

*Workspace optimization* is therefore gaining attention of especially businesses. The term workspace optimization, or similar terms as *workplace optimization* and *workspace utilization*, are used to describe techniques that enable monitoring and tracking occupants in buildings. This information is subsequently used to optimize utilities and resources in the building, or to predict future occupation levels. In academic publications and business whitepapers the following benefits of workspace optimization are stated:

1. It provides an understanding in how a building is used, which allows to make decisions for long-term capacity planning (Serraview, 2015).
2. By collecting occupancy-data to the desk level, employees are able to find vacant desks and rooms in the building on busy days (Serraview, 2015).
3. By collecting data on an individual level, employees can find where their colleagues are located in the building (Serraview, 2015).

4. The energy consumption of the building can be optimized, e.g. by closing unused floors on quiet days (Nguyen & Aiello, 2013; Paola et al., 2014).
5. Security of the building and emergency situations can be handled better and more easily by getting insight in the number of employees and their exact location (Hitiyise et al., 2016; Nyarko & Wright-Brown, 2013).

No formal definition of workspace optimization is found in academic literature, therefore the following definition will be used in this thesis:

Definition: *Measuring, monitoring and predicting building occupancy through IoT devices, and using this information to optimize workspaces*

Based on this definition, workspace optimization consists of the following aspects:
1. Measure occupancy in buildings
2. Monitor occupants in buildings (localize individuals)
3. Predict occupancy in buildings
4. Resources allocation in buildings (suggest workspaces, find vacant desks/rooms, track individuals)

**Enablers for workspace optimization**

Workspace optimization has become possible by three developments over the years. Firstly, there is the significant cost-reduction and exponential improvement of sensing equipment that allows huge numbers of sensors to be placed in e.g. buildings with relatively low costs (Tully, 2015). Secondly, the smart city vision acts as a catalyst to place sensors and actuators in the 'fabric' of urban environments, such as buildings (A. Greenfield, 2006). By doing this, buildings become 'smarter' and it becomes possible for facility managers to monitor and improve resources based on the collected data (Intel, 2015; Kejriwal & Mahajan, 2016). At last, exponential improvements in cloud computing and machine intelligence have enhanced the analytical capabilities that are needed to analyze the data that are collected effectively (Y.-K. Chen, 2012; Tyagi et al., 2014).

**Prior work on workspace optimization**

Even though workspace optimization has various, mainly practical, advantages, academic research that considers how such a solution can be designed and implemented is scarce. Current research is mainly focused on occupancy measuring techniques that make it possible to estimate the number of employees in buildings. Various approaches are proposed and discussed, considering the use of different devices, assumptions, and objectives (Akkaya, Guvenc, Aygun, Pala, & Kadri, 2015). Techniques that are used for the measurement of occupants are varying, from simple counting of DHCP leases (Melfi et al., 2011) to more advanced techniques, such as machine learning (Dong & Andrews, 2009; Lam et al., 2009) and Markov chains (V. Erickson, Carreira-Perpinan, & Cerpa, 2012).
One common denominator in these studies is that they state the following four requirements for occupancy measurement techniques: *Non-intrusiveness*, *low costs*, *high accuracy,* and *privacy preserving*.

1. *Non-intrusiveness* – non-intrusiveness is used to depict a system that does not require the installation of new, intrusive infrastructure (D. Chen, Barker, Subbaswamy, Irwin, & Shenoy, 2013; Yang, Li, Becerik-Gerber, & Orosz, 2012c).
2. *Cost* – each device or sensor that is added costs money, whereas often an affordable system is desired. Thus, it is often preferred to rely on the existing infrastructure and add only low-cost devices and sensors when needed to improve the accuracy (Fierro, Rehmane, Krioukov, & Culler, 2012; Ghai, Thanayankizil, Seetharam, & Chakraborty, 2012; Lam et al., 2009).

3. *Accuracy* – accuracy is intertwined with cost and intrusiveness, since adding lots of devices (e.g. various sensors and camera's) improve the accuracy, but also significantly increases costs and intrusiveness (Akkaya et al., 2015).
4. *Privacy* – *t*he privacy constraint is about identifying and recording personal identities of employees. Such information often needs to be anonymized (Yang, Li, Becerik-Gerber, & Orosz, 2012a).

Some studies go further than just measuring occupancy in the building, and also discuss monitoring occupancy by localizing *where* occupants are in the building. However, these studies are mostly performed in small-scale test settings, such as research labs. Studies that discuss the prediction of occupancy and discuss resource allocation are scarce. Akkaya et al. (2015) have published a review paper in which existing literature on occupancy modeling and monitoring for smart buildings is reviewed, based on the data source and technique that is used. These findings are adapted for this study and extended by assessing whether these studies discuss possibilities for workspace optimization, as defined in this thesis. This review is needed to get a better understanding of the state-of-the-art in this field.

Based on the definition of workspace optimization, the criteria that are used to review these studies, are presented in Table 1.

| **Discussed in study** | **Criterion** | | | |
|---|---|---|---|---|
| | **Occupancy measuring** | **Occupancy monitoring** | **Occupancy prediction** | **Resource allocation** |
| Count the number of people in the building | X | | | |
| Localize occupants in the buildings | | X | | |
| Predict future occupancy levels in a building / space | | | X | |
| Suggest workspaces based on occupancy, track individual occupants | | | | X |

*Table 1 – criteria for literature review of workspace optimization*

These criteria are used to conduct a literature review on workspace optimization. An 'X' in the column of the criterion indicates that this criterion is discussed in the study. The outcomes of this review are displayed in Table 2.

| **Study** | **Data source** | **Techniques** | **Occupancy measuring** | **Occupancy monitoring** | **Occupancy prediction** | **Resource allocation** |
|---|---|---|---|---|---|---|
| "Zone-level Occupancy Counting with Existing Infrastructure" (Fierro et al., 2012) | WiFi, TCP dump | Passive Localization | X | X | | |
| "Sentinel: occupancy based HVAC actuation using existing WiFi infrastructure within commercial buildings" (Balaji et al., 2013) | WiFi, AAA WiFi logs | Zone-based localization | X | X | | |
| "Occupancy detection in commercial buildings using opportunistic context sources" (Ghai et al., 2012) | WiFi, Calendars, IM Clients | Regression & Classification | X | | | |
| "Cloud based passive building occupancy characterization for attack and disaster response" (Nyarko & Wright-Brown, 2013) | WiFi, Sensor, Cloud schedules | Histogram | X | X | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| "Measuring building occupancy using existing network infrastructure" (Melfi et al., 2011) | WiFi, Sensor, DHCP Leases | Simple Counting | X | X | | |
| "Occupancy Modeling and Prediction for Building Energy Management" (V. Erickson et al., 2012) | Camera | Markov Chain | X | | X | |
| "OBSERVE: Occupancy-based system for efficient reduction of HVAC energy" (V. Erickson, Carreira-Perpinan, & Cerpa, 2011) | Camera | Markov Chain | X | | X | |
| "Building occupancy detection through sensor belief networks" (Dodier, Henze, Tiller, & Guo, 2006); | Sensor, Telephone sensor | Bayesian Network | X | X | | |
| "Occupancy detection through an extensive environmental sensor network in an open-plan office building" (Lam et al., 2009) | Sensor | Machine learning | X | | | |
| "An information technology enabled sustainability test-bed (ITEST) for occupancy detection through an environmental sensing network" (Dong et al., 2010) | Sensor | Machine learning | X | | | |
| "A Multi-sensor Based Occupancy Estimation Model for Supporting Demand Driven HVAC Operations" (Yang et al., 2012a) | Sensor | Neural Network | X | X | | |
| "A design model for building occupancy detection using sensor fusion" (Ekwevugbe, Brown, & Fan, 2012) | Sensor | Neural Fuzzy Inference | X | | | |
| "A sensor-utility-network method for estimation of occupancy in buildings" (Meyn et al., 2009) | Sensor, Camera | Extended Kalman Filter | X | X | | |
| "A Non-Intrusive Occupancy Monitoring System for Demand Driven HVAC Operations" (Yang et al., 2012c) | Sensor | Neural Network | X | | | |
| "Non-Intrusive Occupancy Monitoring using Smart Meters" (D. Chen et al., 2013) | Sensor | Clustering | X | | | |

*Table 2 – Literature review Workspace Optimization*

From the literature review in Table 2, the following can be inferred: current research consists of mainly small-scale experiments in which occupancy estimation techniques are discussed, mostly with the objective to enable energy savings. No mention of resource allocation is found in the sense that 'the building' is able to suggest workspaces based on the collected data, in order to cope with the dynamics of office occupation and the practical issues that follow from this. Also, measuring occupancy and monitoring occupants can be performed through various techniques, the possibilities are numerous, depending on the objective. But even then, these techniques have varying results. A structured design or architecture that can be used to 'easily' design and implement a solution for *workspace optimization* is lacking.

**Sub conclusion section 2.1**

In short, workspace optimization becomes interesting to cope with the change of the current working landscape, in which building occupancy becomes more dynamic and unpredictable. Current academic literature is mainly focused on measuring occupancy and monitoring occupants is small-scale experiments. Various techniques and data sources are discussed by the researchers, but due to the enormous possibilities, it is difficult to design and implement such a solution: no guidelines, framework or architectures for workspace optimization are found in current literature.

Based on these findings, the following knowledge gap is stated:

*KG 1: There is a lack of academic research on workspace optimization, a structured design / architecture that can be used to design and implement such a solution is missing*

## 2.2. Smart cities and smart buildings

The second concept that is interesting for this study is *smart cities and smart buildings*. Reason for this is the smart city vision being one of the three enablers for workspace optimization, as discussed in chapter 2.1. In this vision, sensors are increasingly embedded in e.g. buildings, resulting in smart buildings.

### *2.2.1. Smart cities*

The notion of smart cities is commonly used to describe cities in which pervasive and ubiquitous computing are increasingly embedded (Kitchin, 2014). The terms pervasive and ubiquitous computing were popularized by Weiser (1991), who used them to refer to computers that are everywhere, network connected, and invisibly around humans (Hui, Sherratt, & Díaz Sánchez, 2016). One of the main drivers for the transformation of cities is rapid urbanization, because enormous growth of inhabitants leads to all sorts of problems and 'messiness' (Johnson, 2008). Some researchers even state that smart cities are critical for sustainable development to alleviate the challenges that come from this rapid urbanization (Lilis, Conus, Asadi, & Kayal, 2017). Challenges of the enormous growth are mainly difficulties in waste management, scarcity of (public) resources, traffic congestions, and environmental issues due to pollution (Chourabi et al., 2012). Also inadequate and deteriorating infrastructures, energy shortages, and the demand for better economic opportunities and social benefits are named as challenges (Washburn & Sindhu, 2009).

The concept of smart cities is not new; research in this area has been ongoing for more than two decades, with researchers focusing on the consequences of information and communication technologies (ICTs) for e.g. nature, urban infrastructure, management, and everyday life (Kitchin, 2014). Throughout the years, various terms have been used by researchers to describe this concept, see Table 3 for an overview of terms that have been used.

| 'Smart city' synonym | Coined by |
|---|---|
| Wired cities | Dutton, Kraemer, & Blumler (1987) |
| Cyber cities | Graham & Marvin (1999) |
| Digital cities | Ishida et al., (1999) |
| Intelligent cities | Komninos (2002) |
| Sentient cities | Crang & Graham (2007); Shepard (2011) |

*Table 3 - Terms used to describe 'smart cities'*

Even though various terms have been used in previous years, nowadays the term 'smart city' is widely adopted – not only by academia, but also by businesses and government. However, despite the term being commonly known, there is no formal and widely accepted definition of a smart city among practitioners and academia (Chourabi et al., 2012; Kitchin, 2014; Zanella et al., 2014). Chourabi et al. (2012) have conceptualized the term by discussing several definitions that have been used by researchers. In Table 4 a few of these definitions are reconstructed.

| Definition | Defined by |
|---|---|
| "A city well performing in a forward-looking way in economy, people, governance, mobility, environment, and living, built on the smart combination of endowments and activities of self-decisive, independent and aware citizens." | Giffinger (2007:10) |
| "Connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city" | Hall, Bowerman, Braverman, Taylor, & Todosow (2000) |
| A city "combining ICT and Web 2.0 technology with other organizational, design and planning efforts to de- materialize and speed up bureaucratic processes and help to identify new, innovative solutions to city management complexity, in order to improve sustainability and livability." | Toppeta (2010) |
| "The use of Smart Computing technologies to make the critical infrastructure components and services of a city—which include city administration, education, | Washburn & Sindhu (2009) |

| |
|---|
| healthcare, public safety, real estate, transportation, and utilities—more intelligent, interconnected, and efficient” |

*Table 4 – Definitions of smart cities*

Interestingly, these four definitions illustrate that researchers are still struggling to clearly define the term smart city. Some researchers define it by focusing on the *what;* broad implications of smart cities for society, whereas other researchers define it by focusing on the *how*; by combining ICT and web technologies/smart computing technologies to enable this.

Despite the lack of a widely supported definition, researcher are more consentient on the objective of a smart city: *“the final aim is to make a better use of the public resources, increasing the quality of the services offered to the citizens, while reducing the operational costs of the public administrations”* (Zanella et al., 2014:22). This is done by composing urban places with ‘everyware’ – building pervasive and ubiquitous computing in the fabric of urban environments (A. Greenfield, 2006).

Hui et al. (2016) provide a visual overview of a typical smart city, see Figure 4. In this overview, the enabler for smart cities is placed in the center: Internet of Things (IoT). IoT is a novel paradigm in which *things*, such as sensors and actuators, are able to interact with each other and *cooperate* (Atzori, Iera, & Morabito, 2010; Miorandi et al., 2012). In the smart city vision, Zanella et al. (2014:22) name this *urban IoT*, with which they mean a *“communication infrastructure that provides unified, simple, and economical access to a plethora of public services, thus unleashing potential synergies and increasing transparency to the citizens.”*

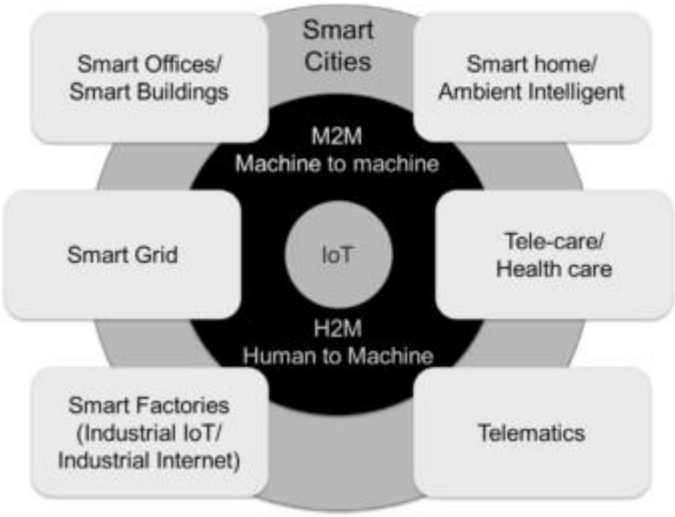



*Figure 4 – overview of a typical smart city (Hui et al., 2016)*

**Benefits of smart cities**
Using IoT in cities has numerous potential benefits, mainly regarding management and optimization of traditional public services (Zanella et al., 2014). Various examples are mentioned by researchers. One example is optimized energy usage by balancing power from power plants and in-house power sources, such as solar panels (Hui et al., 2016). Another example of optimization in smart cities is optimized traffic flows in which traffic is measured of various points and traffic lights are adjusted based on the number of cars on the road (Washburn & Sindhu, 2009). In general, benefits are gained by measuring ‘things’ that were not measured before, and using this information to optimize these ‘things’ (Washburn & Sindhu, 2009; Zanella et al., 2014).

**Barriers for smart cities**
Albeit research on smart cities or similar concepts is ongoing for more than two decades and the potential benefits are numerous, the smart city market has not yet taken off (Zanella et al., 2014). Three reasons are provided for this; a high number of involved stakeholders, non-operability between solutions, and lack of clear business value.

First of all, there is the political dimension. As numerous stakeholders need to be involved when ‘everything’ needs to be connected in a city, the attribution of decision-making power is an obstacle so far. Chourabi et al. (2012) also state the importance of management and organization in smart city initiatives. The authors argue that a smart city can be seen as a large-scale IT project, and that issues regarding management and organization are always important to overcome in order to be successful.

The second reason is more technical; non-interoperability of heterogeneous technologies that are currently used in urban developments hinder that solutions work together. This issue is also pressed by Gubbi et al. (2013), who see this as a barrier for IoT solutions is general; due to differences in approach of applications and use cases there is the threat that the IoT devices remain isolated and cannot communicate with each other effectively. This results in 'networks of things', or 'intranet of things' (Duarte & Ratti, 2016) instead of the (fully connected) Internet of Things. The issue lies in the lack of architectural standards for IoT (Weyrich & Ebert, 2016).

The third reason is that a clear business model is still lacking, huge investments in public services are needed to realize the smart city vision. Therefore, Zanella et al. (2014) argue that services should be developed that *"conjugate social utility with very clear return on investment, such as smart parking and smart buildings, and will hence act as catalyzers for the other added- value services"*.

#### *2.2.2.Smart buildings*

Based on the findings in previous sections, smart buildings will be discussed next, because Hui et al. (2016) have clearly stated that smart buildings are a *building block* for smart cities, and that smart buildings/offices are a good starting point for smart cities, as the scale is smaller and the return-on-investment can be explicated more easily (Zanella et al., 2014). Next to that, by embedding sensors that are needed for workspace optimization in buildings, buildings become 'smarter', resulting in smart buildings.

As with smart cities, research in the area of smart buildings is ongoing for several years, and several terms are used to describe the same concept, see Table 5. Despite the fact that various researchers have described such buildings and defined use cases, Batov (2015) argues it is important to understand what makes a building smart or intelligent. Reason for this is that often smart features are confused with just automation, such as using a remote control for certain devices, or predefined behavior of some systems. Therefore, the following definition by Mozer (2005) about smart homes is according to Batov (2015) most applicable: *"Instead of being programmed to perform certain actions, the [building] essentially programs itself by monitoring the environment and sensing actions performed by the inhabitants (e.g., turning lights on and off, adjusting the thermostat), observing the occupancy and behavior patterns of the inhabitants, and learning to predict future states of the [building]".* Thus, a true smart building learns from its occupants and iniates its own actions.

Various terms have been used to describe 'smart buildings' over the years, but the terms smart buidling and intelligent building have become common terms for these initatives in recent years – not only in academia, but also in whitepapers from businesses (Intel, 2015; Kejriwal & Mahajan, 2016).

| 'Smart building' synonym | Coined by |
|---|---|
| Adaptive home | Mozer (2005) |
| House_n | Pacik (2000) |
| The aware home | Kidd et al. (1999) |
| MavHome | Cook et al. (2003) |
| Smart factories | Shrouf, Ordieres, & Miragliotta (2014) |
| Intelligent building | Lilis et al. (2017); Wong, Li, & Wang (2005) |

*Table 5 - other terms used to describe 'smart buildings"*

Gartner (2015) estimates that *"smart commercial buildings will be the highest user of Internet of Things (IoT) until 2017, after which smart homes will take the lead with just over 1 billion connected things in 2018".* The role of IoT in smart buildings is to track e.g. motion, air pressure and temperature, and then *"autonomously sense, communicate, analyze, and act or react to people or other machines in a* *nonintrusive manner"* (Kejriwal & Mahajan, 2016:4). In recent years, the need for innovations in the building domain of smart cities was mainly focused towards sustainability and energy efficiency, most likely because gains in this area are most obvious and quantifiable (Lilis et al., 2017). Other areas, such as workspace optimization, are perhaps less quantifiable and obvious, which might explain the lack of academic research in this area. Nonetheless, current and new business expect huge potential of integrating IoT devices in buildings, thus firms were quick to enforce their new standards, especially major industrial firms. However, due to both the novelty and the huge market potential, smaller firms and startups started to offer their own solutions as well, with the result that *"as more and more parties entered with their own, proprietary implementations, it started to become a Babel tower where hardly any integration between manufacturers' systems was possible"* (Lilis et al., 2017:474). Thus, as with smart cities, the need for industry standards and interoperability between solutions is put forward again.

**Sub conclusion section 2.2**
In short, the embedment of IoT devices in buildings will increase significantly in coming years. However, there is the threat that smart buildings are becoming a 'Babel tower' if no standards and interoperability of solutions are offered. Vendors are not cooperating, but pushing their own standards instead. This hinders the development of smart cities for which interoperability is key. Next to that, there is a need for a common understanding between multiple stakeholders that are involved, this 'political dimension' has hindered development of smart cities and smart buildings for more than two decades already.

The following knowledge gaps are stated:
*KG 2: Due to differences in approach of IoT use cases, there is the threat that the IoT devices and solutions remain isolated and cannot communicate with each other effectively, reducing potential for smart cities and smart buildings*

*KG 3: There is a need for common understanding between stakeholders that are involved in smart cities and smart buildings*

## 2.3. Internet of Things Architectures

From the previous sections can be inferred that workspace optimization is enabled by embedding IoT devices in buildings, but that there is no structured design or architecture of how such a solution should be developed and implemented. Numerous techniques and approaches exist, based on a variety of data sources, but these study are mainly isolated, and provide not much clarity. Next to that, there is a need for interoperability of solutions and a common understanding between the involved stakeholders, otherwise development of smart buildings will be hindered. Therefore, Internet of Things Architectures are interesting to discuss. This will be done by first discussing IoT in general, followed by IoT architectures.

### *2.3.1. Internet of Things*

The Internet of Things (IoT) is a paradigm that has gained a lot of traction among researchers in recent years. In 1999 the term was introduced by Kevin Ashton in the description of connected devices in supply chain management, but since then its application in a variety of fields has been discussed, such as healthcare, energy, and resource optimization (Ashton, 2009; Gubbi et al., 2013; Weyrich & Ebert, 2016). In the IoT vision, *"electronics will be embedded into everyday physical objects, making them 'smart' and letting them seamlessly integrate within the global resulting cyber-physical infrastructure"* (Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012:1497). In recent years, IoT is being used as an umbrella term for more than just smart objects; also services and applications that are connected through the internet are described by this. These smart things can also communicate with other resources that are available in the web, resulting in added value for the end-user and applications (Cavalcante, Alves, Batista, Delicato, & Pires, 2015). As such, Garner has included IoT in each issue of their *top 10 strategic trends for technology* since 2012 (Gartner, 2016b).

Despite the lack of a universal definition of IoT, researchers agree that the semantic meaning of Internet of Things is *“a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols”* (Atzori et al., 2010:2788). This statement explicates how the ‘Internet’ and the ‘Things’ are connected. The first part is related to the ‘things’, whereas the second part is related to the internet, which is defined as: *“The world-wide network of interconnected computer networks, based on a standard communication protocol, the Internet suite (TCP/IP)”* (EPoSS, 2008).

The core concepts underlying IoT are not new, they have been around for years. The ‘things’ are small devices that are connected and collect data, such as RFID tags, (wireless) sensors, and actuators. RFID and sensors networks are already being used for some years to track e.g. containers (Narsoo, Muslun, & Sunhaloo, 2009) and animals (Voulodimos, Patrikakis, Sideridis, Ntafis, & Xylouri, 2010). Also machine-to-machine communication is not new, however, the concept of IoT is evolutionary as sensors are becoming increasingly smaller, computing power is significantly increasing, and the number and nature of devices are growing dramatically, as well as the way they are connected with each other across the internet. Everyday devices that were originally not designed to be connected, such as lightning, smoke detectors, and door locks, have now potential to communicate with each other (Whitmore, Agarwal, & Da Xu, 2015). At this moment, RFID is still leading the technologies that are driving the IoT vision, nonetheless an extensive range of devices, services, and technologies will inevitably build on the IoT, e.g. Near Field Communication (NFC), and Wireless Sensor and Actuator Networks (WSAN) (Presser & Gluhak, 2009).

**Internet of Things challenges**

Even though IoT is growing significantly, there are still various challenges for that need to overcome. First of all, IBM’s chief executive for IoT states that IoT is in a bubble phase, and that companies should thus be aware of the true added value it can provide for the end consumer. Gartner supports these findings and places IoT at the start of ‘inflated expectations’ in their annual hype cycle for emerging technologies – mainstream adoption will take at least 5-10 years (Gartner, 2016a).

Next to that, some researchers argue that a clear approach and models for utilizing the enormous amount of data that result from extensive connectivity of large numbers devices is currently lacking (Noronha et al., 2014). A strong focus on e.g. data processing and analytics is needed from the start to gain value from data that is collected by IoT devices *“Collecting data isn't enough for businesses investing in Internet of Things projects […] they'll have to incorporate robust analytics”* (Burns, 2014). This barrier will be assessed further in section 2.3.2.

At last, in order to improve the connectivity of IoT devices, a huge number of initiatives are ongoing to develop standards (Atzori et al., 2010; Y.-K. Chen, 2012). However, as was already discussed in chapter 2.2, early technological developments are often driven by small and medium-sized enterprises (SMEs), who are able to innovate much easier. Their focus is mostly on a product or service with a narrow scope (Bassi et al., 2013). These fragmented efforts towards standardization is slowing down both development of solutions and interoperability between these solutions. Therefore, standards that are being pushed by agencies are preferred, because they are better able to unify the developments (Vermesan & Peter Friess, 2013). Otherwise, the lack of standardization leads IoT platforms that adopt different programming models that are not compatible with each other, not properly address functional and non-functional requirements, and neglect privacy and security issues (Cavalcante et al., 2015). In the context of smart buildings, it becomes apparent that interoperability between devices of different vendors is not always straightforward, because they were not based on common guidelines from the start (Lilis et al., 2017).

One way to overcome these issues, such as a lack of standardization, is the adoption of reference architectures, because reference architectures define guidelines and basic concepts that can be used for the construction of concrete architectures (Cavalcante et al., 2015; Karzel, Marginean, & Tran, 2016). Reference architectures provide an initial set of building blocks and afford a substance to improve the adoption of IoT solutions (Cavalcante et al., 2015). Reference architectures will be discussed in section 2.3.3.

### *2.3.2.Data Management in Internet of Things Architectures*

One IoT challenge that is relevant for this study is the lack of data management in the system design. At this moment, organizations' focus is more on connecting the most devices, whereas a focus on their capabilities regarding data (data integration, storage, processing and analytics) from the start of the system design already is needed to gain the most value (Cavalcante et al., 2015; Noronha et al., 2014; Zdravkovi et al., 2016). These capabilities are often mentioned under the term *data management*: *"Much of the IoT initiatives are geared towards manufacturing low-cost and energy-efficient hardware for these objects, as well as the communication technologies that provide objects interconnectivity. However, the solutions to manage and utilize the massive volume of data produced by these objects are yet to mature"* (Abu-Elkheir, Hayajneh, & Ali, 2013:12). However, this is not straightforward, integrating capabilities for data management in IoT Architectures is described as one of the biggest challenges for IoT (Gubbi et al., 2013).

More specifically, in order to capitalize the wide range of data that is collected by IoT devices, organizations must overcome in particular the following challenges (Noronha et al., 2014):

- Integrating and storing data from multiple sources
- Processing and analyzing data to effectively identify actionable insights

Additional challenges regarding privacy arise when sensitive data is collected and handled (D'Acquisto et al., 2015). Several privacy enhancing techniques are mentioned by researchers to cope with these additional challenges.

Based on various *data lifecycle management* descriptions, the following becomes clear: (1) The terms for data management are often used interchangeably or defined variously, (2) the sequence of these capabilities is varying (Abu-Elkheir et al., 2013; TATA, 2017; U.S. Geological Survey, 2015), and (3) integration & storage, as well as processing & analytics are tightly related to each other, or even taking place simultaneously.

Therefore, a definition of the terms will be provided first, before they are assessed. See Table 6 for the definitions:

| |
|---|
| **Integration**: *"the process of combing data residing at different sources, and providing the user with a unified view of these data"* (Lenzerini, 2002:233). |
| **Storage**: *"actions and procedures to keep data for some period of time and/or to set data aside for future use, and includes data archiving and/or data submission to a data repository"* (U.S. Geological Survey, 2015). |
| **Processing**: *"any set of structured activities resulting in the alteration or integration of data"* (U.S. Geological Survey, 2015). |
| **Analytics**: *"actions and methods performed on data that help describe facts, detect patterns, develop explanations, and test hypotheses"* (U.S. Geological Survey, 2015). |

*Table 6 – Definitions of capabilities for data management*

#### Integrating and storing data from multiple sources

As IoT systems are often typified by a variety in devices, as well as the huge volume of data these devices collect, data integration becomes increasingly challenging (Abu-Elkheir et al., 2013). At the same time, it also becomes more important, as various data sources need to be integrated, which is needed before data can be processed and analyzed (Noronha et al., 2014).

Traditionally, data integration took place by copying it to a central location, such as a data warehouse (Lans, 2014), which is defined as an *"integrated, time-varying, non-volatile collection of data that is used primarily in organizational decision making"* (Chaudhuri & Dayal, 1997:1). Before the data is stored there, (multiple) integration steps can be applied to it to optimize the data that is stored, e.g. by discarding 'noise' or by renaming fields. This is called *schema-on-write* (Brennan & Bakken, 2015). Due to this process, data that is stored in a data warehouse is mostly structured. Business users access the data through data marts that are retrieved from the data warehouse; "subject-oriented" subsets of the data for a specific purpose, e.g. the marketing datamart consists of only data that is relevant to the marketing department (Chaudhuri & Dayal, 1997).

In IoT systems, it becomes challenging to define a schema from the start, as these systems are relatively dynamic (e.g. by identifying new use cases on the already collected data). Thus, organizational requirements are changing. Data warehouses are not so dynamic, as they have to be designed specifically with organizational requirements in mind: a schema needs to be defined on beforehand. This means that data which might be useful in the future is not stored, as it does not fit the schema, it is thus very goal-driven (Furlow, 2001; Haller, 2010). For this reason, *data lakes* are becoming increasingly popular as an alternative for data warehouses in recent years. The term Data Lake has been coined by James Dixon in 2010, he describes it as follows: *"If you think of a datamart as a store of bottled water – cleansed and packaged and structured for easy consumption – the data lake is a large body of water in a more natural state. The contents of the data lake stream in from a source to fill the lake, and various users of the lake can come to examine, dive in, or take samples"* (Dixon, 2010). Thus, in a data lake, mostly raw, unstructured data is stored. A schema is only applied when a user desires to make use of the data: *schema-on-read*. This leads to an *"ever-evolving data model that grows and is modified as new data are encountered and obtained, rather than rejecting data because they do not meet an existing schema"* (Brennan & Bakken, 2015:479)

In both data warehouses and data lakes, the data is stored and integrated in one place, *centralized*. Advantages of this are that all data is in one place, simplifying both access and use. Also, there is higher data quality as there is no confusion over duplicate data sets, which makes it easier to maintain. Disadvantages of data centralization are that all the data needs to be moved to one place. If data needs to be integrated and stored from e.g. geographically dispersed location in a central data center, this can be troublesome for the network and performance (Lockner, 2015). When the situation is like this, *data decentralization* is more useful. Data centralization adopts the approach that data remains at the place in which it is created: the integration of various data sources happens at the source location. An example is a large organization with multiple locations, each office has its own data ecosystem that is independent from the one of the main office. Advantages of this are e.g. performance gains, as insights can be derived and act upon more quickly at the location itself. Disadvantages are e.g. a lack of standardization, a lack of common enforcement of data governance policies, and redundant infrastructures (Lockner, 2015).

**Processing and analyzing data to identify actionable insights**

Next to the type of data storage and integration, it is also important to consider the location at which the data processing and analytics will be performed, some researchers even state this as a primary design concern in IoT systems (Abu-Elkheir et al., 2013; Kulkarni, Kute, & More, 2016). Reason for this is that data processing and analytics are needed to retrieve actionable insights. *"Without this crucial step, data remains just 'data'"* (Noronha et al., 2014:9).

Also for processing and analytics two approaches can be distinguished: *centralized* and *decentralized*. Centralized data processing was introduced in early IoT approaches as a way to make it easier to upgrade and reprogram IoT devices, as the application logic is moved to a separate (centralized) server instead of being into the devices' firmware (Wang, Lee, Murray, & Qiao, 2016). As stated before, this has the consequence that all the data needs to be transported to a centralized storage to enable processing tasks and following steps, e.g. data analytics and visualization. As discussed, even though this is positive for upgrades, moving all the (raw) data to a central place can be troublesome for the network (Gregorio, 2015). Decentralized processing has therefore gained traction in recent years. By moving the processing steps towards the devices, the volume of data that needs to be transported to a centralized storage is reduced (Abu-Elkheir et al., 2013). Especially for IoT systems large added values are promised by decentralizing processing capabilities towards the 'edges of the Internet' because data is often collected continuously and decisions need to be made in real-time (Gregorio, 2015).

Very much related to centralized and decentralized data processing is the design concern for to perform these steps in batches, or in real-time (Strohbach, Ziekow, Gazis, & Akiva, 2015). For the former, data is processed and analyzed in batches, e.g. each 5 minutes. This is often used when the response time is less important (Gartner, 2017; Strohbach et al., 2015). The actual processing that is used for batch processing uses a computational framework such as Hadoop's MapReduce (Dixon, 2010; White, 2012) or Hama's Bulk Synchronous Processing Framework (Seo et al., 2010). In real-time processing, data is processed instantly as it is collected. Solutions for this are often referred to as *stream processing* or *complex event processing (CEP)*. In CEP frameworks, logic is implemented in the form of queries or rules over continuous data flows. Data is processed in an event-driven manner, contrasting to batch processing which is triggered either by request or by a schedule (Strohbach et al., 2015). CEP is used when fast analysis of incoming information is needed. Several CEP solutions emerged in recent years is both academia and industry, such as TelegraphCQ (Chandrasekaran et al., 2003) and STREAM (Motwani et al., 2003).

Thus, several design choices for the integration of data capabilities in IoT systems exist. IoT architects need to consider the options carefully in the start of the system design, instead of performing these steps 'ad-hoc', which is the current trend. Figure 5 provides an overview of options for data capabilities that are discussed in this section.

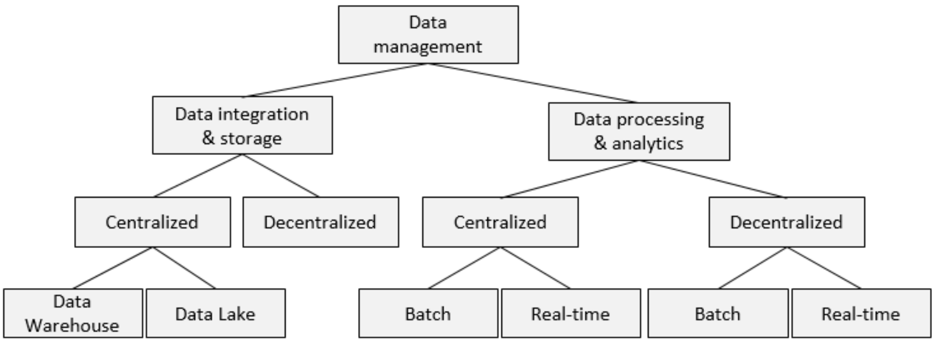


*Figure 5 – Design choices for data capabilities in IoT systems*

**Handling sensitive data**

By collecting, processing and analyzing personal data, which might be needed for a workspace optimization solution, privacy concerns are raised. Therefore, an important consideration in the design of architectures should be which data management design choices can be taken to preserve the privacy of users. These concerns are acknowledged by researchsers, as studies have been undertaken to *"allow for the benefits of analytics without invading individuals' private sphere. It is of utmost importance to draw the limits of big data processing and integrate the appropriate data protection safeguards in the core of the analytics value chain"* (D'Acquisto et al., 2015:5).

Privacy is a broad concept that has various definitions (Gürses, Berendt, & Santen, 2008), but in this context it refers to the *"concealment of personal information as well as the ability to control what happens with this information"* (Weber, 2010). Privacy concerns in Internet of Things and big data are discussed for many years already, resulting in various academic approach to this, e.g. by describing potential threats and mitigation strategies (Khoo, 2011), by providing an overview of privacy enhancing technologies (Hoepman, 2014), and by the creation of a legal framework (Weber, 2010).

In recent research, the trend is not to consider big data and IoT as being *versus* privacy, but as big data and IoT *with* privacy. That is, integrating measures for the preservation of privacy in the system design already: *privacy by design*. This is process that involves various technological and organizational components that integrate privacy enhancing and data protection principles (D'Acquisto et al., 2015; Hoepman, 2014). Several privacy enhancing design strategies are described by D'Acquisto et al. (2015) and Hoepman (2014), see Table 7.

| **Privacy by design strategy** | **Description** |
|---|---|
| Minimize | The amount of personal data that is collected, integrated and processed is kept to a minimal amount |
| Hide | Personal data and their interrelationships should be hidden from plain view |
| Separate | Personal data should be processed in a distributed fashion, in separate compartments whenever possible |
| Aggregate | Personal data should be processed at the highest level of aggregation and with the least possible detail that is still useful |
| Inform | Data subjects should be informed whenever their data is processed |
| Control | Data subjects should be able to control their personal data |
| Enforce | A privacy policy that is compatible with legal requirements should be in place |
| Demonstrate | Compliance with legal requirements and the privacy policy can be demonstrated |

*Table 7 – Privacy by design strategies* (D'Acquisto et al., 2015; Hoepman, 2014)

In the context of data management in IoT systems, these privacy enhancing strategies have the following consequences:

*Data collection, integration and storage*

- Minimize: In the system design already, there should be a precise definition what personal data is needed for the IoT system, as well as the data retention period. There should be processes in place that excludes unnecessary personal data from the collection mechanisms (D'Acquisto et al., 2015).
- Hide: access controls are important for the protection of personal data, access should only be granted to trusted persons. Encryption is also important for the stored data (D'Acquisto et al., 2015).
- Aggregate: sometimes, personal information is not needed at all, anonymized data is then sufficient for the purpose, e.g. for the calculation of average occupation rates or average time spent in the building (Hoepman, 2014).
- Notice: individuals are notified on the (type of) data that is being collected on them (D'Acquisto et al., 2015).
- Control: consent of the user needs to be obtained before personal data can be processed and analyzed. If individuals do not agree, no data should be collected on them (D'Acquisto et al., 2015).

*Data processing and analytics*

- Aggregate: privacy models and anonymization methods should be applied to preserve data inference. Types of algorithms should be used that are privacy preserving, e.g. classification and clustering. After the algorithm has run, the data source data should not be stored (D'Acquisto et al., 2015).
- Hide: encryption/anonymization are popular techniques for the preservation of privacy, as this hides personal data from plain view, but still enables certain data analytical algorithms to retrieve useful insights, e.g. to create clusters (Hoepman, 2014).
- Separate: analytics in distributed systems can help for the preservation of privacy, as computations happen across different databases, without the need for storing all data in central data warehouses. Only the results can be stored (D'Acquisto et al., 2015).

Thus, the integration of capabilities for data management in IoT architectures is challenges, and becomes even more challenging when privacy is an important aspects. It is therefore important to consider these challenges from the design of IoT systems already.

### *2.3.3.Reference Architectures*

Another IoT challenge that is relevant in this study is the lack of interoperability between IoT solutions, therefore architectures are discussed.

In general, architectures are used to provide an understanding of the important parts in a system, how they work together, and how they interact with their environment. The need for (reference) architectures is motivated by Rozanski & Woods (2011), who describe architectures in the context of software development as a way to comprehend a complex computer system. Because architectures are very useful in the design and development of systems, IEEE has published a standard that provides guidelines on how architectures should be constructed and what is needed for them; the *IEEE recommended practice for Architectural description of software-intensive systems*. They define an architecture with the following definition:

Definition: *"The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution."* (IEEE-SA, 2000:3)

Because architectures are especially useful for communication between the parties that are involved in the development of systems, architectures are designed for the specific needs that these stakeholders have (Rozanski & Woods, 2011). Stakeholders are defined as follows:

Definition: *"A person, group, or entity with an interest in or concerns about the realization of the architecture"* (Rozanski & Woods, 2011:1).

In the IEEE standard for architectures (standard 1471), the following stakeholders are argued to be included in all architectural descriptions: users, acquirers, developers, and maintainers of the system (IEEE-SA, 2000). Each of these stakeholders has specific concerns that are addressed in the architectures as requirements. Non-functional requirements are e.g. performance, reliability, and security (IEEE-SA, 2000).

Definition: *"A concern about an architecture is a requirement, an objective, an intention, or an aspiration a stakeholder has for that architecture"* (Rozanski & Woods, 2011:1).

An important notion on architectures is that it is often impossible to describe a complex system in one, all-encompassing model, therefore Kruchten (1995) described a widely-accepted approach to coping with this, using interrelated architectural views that each describes a separate aspect of the architecture (Rozanski & Woods, 2011). Put together, these views provide a description of the whole system. A view is defined as follows:

Definition: *"A representation of a whole system from the perspective of a related set of concerns"* (IEEE-SA, 2000)

In the specific context of IoT solutions, the need for IoT Architectures is argued by Weyrich & Ebert (2016). They reason that IoT has the potential to provide tremendous value to organizations, however, not many people within organizations have knowledge about the combination of software, IT needs and technology that is needed for such solutions. *"IoT architecture and modeling solutions must connect heterogeneous communities to understand and work together"* (Weyrich & Ebert, 2016:113). According to the authors, there are particular approaches needed for security, maintainability, and sustainability. Reference architectures for IoT help to overcome these challenges.

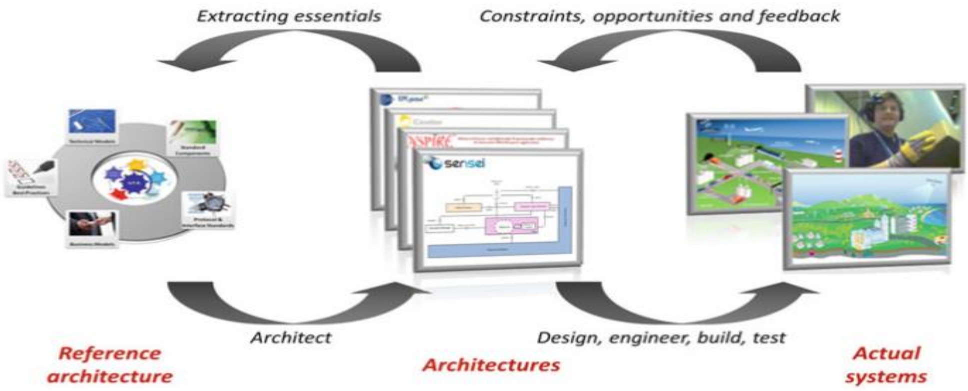



*Figure 6 – relationship between reference architectures, architectures, and actual systems* (Bassi et al., 2013)

Reference architectures provide a description of a system that is more abstract than concrete architectures for actual systems and applications that have been designed with specific choices and constraints. Reference architectures accordingly serve as a blueprint for specific architectures (Muller, 2012). Figure 6 displays the relationship between reference architectures, architectures, and actual systems.

Reference Architectures are especially needed for IoT because IoT applications are currently based on fragmented implementations for specific use cases. Reference architectures prevent 're-inventing the wheel' for already solved problems by providing best practices and essentials, and is especially useful for achieving interoperability between different systems (Muller, 2012). In IoT context, they can be used to design the setup of IoT devices in the system, and their relationship with physical entities, software, and their environment (Bassi et al., 2013).

The need for a structured approach to the development of IoT solutions has been recognized by both researchers and businesses, and has resulted in various initiatives towards standardized references architectures for IoT, Weyrich & Ebert (2016) have described these initiatives and their status as of June 2015. In Table 8 these findings are extended and the status of the initiatives is updated as of March 2017.

| Initiative | Description | Status | URL |
|---|---|---|---|
| Reference Architecture Model Industrie 4.0 (RAMI 4.0) | IoT Reference Architecture for Industry 4.0, a specific focus on industries, smart factories | Version 1 as of March 2017 **Not finished** | www.zvei.org/en /association/specialist - divisions/automation /Pages/default.aspx Version |
| Industrial Internet Reference Architecture (IIRA) | Standards-based reference Architecture for the Industrial IoT, developed by the Industrial Internet Consortium | Version 1.7 as of March 2017 **Not finished** | https://www.iiconsortium.org/IIRA.htm |
| Internet of Things – Architecture (IoT-A) | Developed through a European Lighthouse Project on IoT, the IoT-A consists of a detailed reference model and reference architecture, and includes unified requirements for the creation of domain-specific architectures. | Final architectural reference model published in July 2013. **Finished – Support remains provided by the IoT Forum** | http://www.meet-iot.eu/iot-a.html |
| Standard for an Architectural Framework for the Internet of Things (IoT) | IEEE P2413 project that has the goal to develop a reference architecture based on standards, the goal is to reduce fragmentation. | No publications or documents as of March 2017 **Not finished** | https://standards.ieee.org/develop/project/2413.html |

| | | | |
|---|---|---|---|
| Arrowhead Framework | European project for connecting SOA-based solutions that are based on different technologies. | Pilots released and a few demonstrations as of March 2017<br>**Not finished** | http://www.arrowhead.eu/deliverables/ |
| OTA Framework | Framework by the Online Trust Alliance that consists of 37 principles for IoT solutions, serving as a product development and risk assessment guide. The framework has a specific focus is on security, trust and privacy | Framework released in January 2017, Whitepaper released in March 2017.<br>**Not finished** | https://otalliance.org/initiatives/internet-things |
| WSO2 | Proposed reference architecture by WS02, a company that has expertise in the development of IoT solutions. Aims to provide an effective starting point that covers most of the requirements of IoT systems and projects | Several whitepapers published, no final version released as of March 2017.<br>**Not finished** | http://wso2.com/whitepapers/a-reference-architecture-for-the-internet-of-things/ |

*Table 8 – Initiatives for the development of reference architectures for IoT, adapted from (Weyrich & Ebert, 2016)*

From Table 8 can be inferred that a variety of IoT reference architectures are being developed. Some initiatives, such as RAMI and IIRA have a specific focus on industries, whereas other initiatives focus on specific aspects of IoT solutions, such as being SOA-based (Arrowhead Framework) or having a high need for security, trust and privacy (OTA Framework).

**Sub conclusion chapter 2.3**

In short, IoT sensors are becoming increasingly present in everyday objects, but fragmented efforts towards standardization is hindering adoption. Companies are mainly pushing (their own) standards nowadays, whereas unified standards are needed to unify development. Also, a strong focus on capabilities for data management is needed to attain value in IoT systems from the data that is being collected, instead of only focusing on connecting as many devices as possible. Several design choices are presented that can be used by system designers to make decisions regarding the data management. In particular when sensitive data is collected and, privacy issues arise that need to be handled in the design-phase of IoT systems already. At last, reference architectures, which define guidelines that can be used for the creation of concrete architectures are currently being developed to cope with the lack of architectural standards. However, many initiatives are still ongoing.

The following knowledge gap is stated

*KG 4: A clear focus on capabilities for data management is lacking in IoT solutions, whereas this needs to be taken into account from the start, especially when privacy-sensitive data is collected.*

## 2.4. Chapter conclusion

Based on the previous sections, the following can be concluded. Smart cities and smart buildings have huge potential to make better use of resources and to improve the ‘quality of life’ for occupants by embedding IoT devices (sensors, actuators) throughout the city and buildings. However, current solutions are often non-interoperable, because they are not based on common guidelines and architecture standards. This problem is present with IoT solutions in general, a lack of solutions that are based on standards and common guidelines are a threat for connecting solutions. Several reference architectures are currently in development to overcome this threat.

One use case of IoT devices in buildings is workspace optimization. This field is becoming increasingly relevant, because current solutions to cope with the dynamics of office occupation, such as open floor plans and hot-desking have drawbacks. Practical problems are that employees have difficulties with finding colleagues (who have no designated desks) and finding vacant desks on busy days when occupancy is high. Workspace optimization is a concept that is mostly described in whitepapers as a potential solution to cope with dynamics of office occupation by mitigating these drawbacks. This is done by collecting data through various IoT devices and consequently measuring occupancy in the building to the desk level and allocating resources based on that. Currently, numerous techniques exists for measuring occupancy, these are independently developed and based on varying techniques and data sources. There is no clear architecture for the design and implementation of such a solution, which hinders adoption.

Numerous knowledge gaps have been identified in the literature that has been described in this chapter.

- KG1: There is a lack of academic research on workspace optimization, a structured design / architecture that can be used to design and implement such a solution is missing
- KG2: Due to differences in approach of IoT use cases, there is the threat that the IoT devices and solutions remain isolated and cannot communicate with each other effectively, reducing potential for smart cities and smart buildings
- KG3: There is a need for common understanding between stakeholders that are involved in use cases for smart cities and smart buildings
- KG4: A clear focus on capabilities for data management is lacking in IoT solutions, whereas this needs to be taken into account from the start, especially when privacy sensitive data is collected.

# 3. Research Approach

In this chapter, the findings from chapter 2 will be used to describe the research approach for this thesis. The research approach consists of the following:

- Research strategy
- Data collection
- Data analysis
- Data issues.

Based on the problem exploration, the following problem statement is derived: *workspace optimization has potential to cope with the current dynamics in the working landscape. IoT devices in devices enable this, but an IoT architecture for the design and implementation of workspace optimization is lacking.*

From the theoretical background in chapter 2 can be inferred that there is potential to improve both the development of smart cities and smart buildings, and the development of workspace optimization as a research area by developing an IoT architecture that is based on common grounding. The knowledge gaps that have been derived indicate what else is needed: a common understanding between stakeholders and a clear focus on capabilities for data management in the design-phase. Therefore, the research objective for this study is stated as follows: *design an IoT architecture for workspace optimization that is based on common grounding and integrates capabilities for data management.*

In order to ensure that best practices and guidelines are being used for the creation of the workspace optimization IoT architecture, an IoT reference architecture will be selected to guide this process. The research approach that will be used for the selection of this reference architecture and subsequently, the design of the workspace optimization architecture will be described in this chapter.

## 3.1.Research strategy: Case study

A research strategy is stated to be the most significant decision in the construction of a research design. With a research strategy is meant *"the coherent body of decisions concerning the way in which the researcher is going to carry out the research"* (Verschuren & Doorewaard, 2010:155). A research strategy offers high-level guidance, and is complemented with a research method for performing the specific task. One important requirement for a research strategy is that it should be practically feasible, there should be access to data sources or people.

### *3.1.1.Case study*

A qualitative case study is most fitting for this study, because a rich, in-depth analysis of the phenomenon (in this study: workspace optimization in smart buildings) is needed. In a case study the depth and complexity of a problem is embraced, because this provides insights in the various processes that take place inside that phenomenon and the relationships that exist between relevant aspects of the phenomenon (Johannesson & Perjons, 2014).

An IoT architecture for workspace optimization in smart buildings will be designed through a case study in an existing smart building in Amsterdam. At this moment, there is no solution for workspace optimization in this building, even though this is desired by the building tenant and facility management. For the design of this architecture, input from relevant stakeholders and experts is needed, because the architecture needs to represent their concerns, as discussed in chapter 2. Their concerns are collected as requirements for the architecture. Collecting these requirements from relevant stakeholders in the smart building, and subsequently designing the architecture in that specific setting can be seen as a case study, because the building and the stakeholders are used to gain a richer understanding of the context and the process (Saunders, Lewis, & Thornhill, 2009; Yin, 2003).

#### *3.1.2.Case setting: The Edge*

The case study will be performed in smart building The Edge in Amsterdam. The building is developed by OVG Real Estate and is located in the Amsterdam business district. The doors opened in 2014, with Deloitte as its main tenant (OVG, 2014). The Edge is certified as 'the world's greenest building' and consists of more than 20.000 sensors that collect a variety of data (Wakefield, 2016). As a result of this, the building has been featured in various media outings, such as the BBC (Wakefield, 2016), Bloomberg (Randall, 2015), and the Financial Times (Cox, 2017). Currently, there is no workplace optimization 'feature' in the building, whereas this is desired by the employees.

This case setting is selected because this study is conducted with the cooperation of Deloitte, who is the main tenant of the building. Thus, access to the building, employees in the building, and data sources is offered.

## 3.2.Data collection: Desk study and Interviews

Data will be collected through a desk study, complemented with (semi-structured) interviews. Reason for this is that using more than one method, a 'mixed-methods approach', is helpful in validating the findings (Johannesson & Perjons, 2014).

In the desk study documents regarding IoT reference architectures will be assessed to explore which reference architecture fits this study best. Next to that, project documents of the selected reference architecture, as well as documents of projects that applied this reference architecture before, will be studied.

Following the desk study, semi-structured interviews will be conducted with relevant stakeholders to identify additional requirements for the architecture, as well as to prioritize the requirements. The desk study is further explained in section 3.2.1. The interviews are further explained in section 3.2.2.

#### *3.2.1.Desk study*

The first part of the data will be collected through a desk study. In the desk study, project deliverables of reference architectures will be studied to select one reference architecture. After that, project documents of the reference architecture that has been selected will be analysed to find best practices on using the reference architecture. Further, projects that have used or implemented the reference architecture are studies as well to gain a better understanding of the design process.

These documents will be used to collect:

1. Requirements for the workspace optimization IoT architecture, based on best practices from previous studies
2. Relevant stakeholders that have been used in previous projects, in order to indicate the stakeholders that are relevant for this process.

#### *3.2.2.Semi-structured interviews*

The second part of the data will be collected through semi-structured interviews. Interviews are stated to be the most traditional and commonly used technique for requirements elicitation, because they are very effective in collecting a large amount of data in a small time span (Gunda, 2008; Wohlin, 2005). After the architecture has been designed, additional interviews will be conducted to evaluate the architecture.

In literature three types of interviews are described; unstructured, structured, and semi-structured. Unstructured interviews are mainly conversational, and the interviewer has limited control over the direction of the conversation, because there is no predetermined interview guide. This type of interview thus useful for exploring new ideas when the domain is relatively new and unknown (Saunders et al., 2009; Wohlin, 2005). Structured interviews, on the other hand, are following a somewhat strict sequence of questions that the interviewer has prepared, in order to gather specific information. However, one drawback of structured interviews is that they tend to limit the investigation of new ideas (Saunders et al., 2009; Wohlin, 2005). Semi-structured interviews are a combination of the two; the interviewer has a list of topics/questions that he/she wants to discuss, and these are used to guide the interview. Through the open character of the conversation, new ideas are able to arise and to be discussed (Saunders et al., 2009).

The goal of the interviews in round 1 is twofold: requirement prioritization and requirement elicitation. On the one hand, requirements that have been derived from the desk study will be prioritized by the stakeholders. On the other hand, new ideas and requirements that are not yet covered are will be collected as well. Therefore, semi-structured interviews seem most applicable in this project.

> **Volere requirement templates** have already been used for more than 2 decades in both business and academia to discover, organize, and communicate requirements for various projects (Robertson & Robertson, 2012). Volere templates define atomic requirements; requirements that consists of a collection of attributes to make them measureable. These are explained and displayed in the requirements shell in Appendix B.

Requirements are often structured using *Volere requirement templates*, a common engineering approach for requirements elicitation (Carrez et al., 2013). These will be used in this study as well.

After the architecture has been designed, interviews will be conducted with experts to validate the requirements (round 2). See Figure 7 for a visualization of the data collection methods in this study.

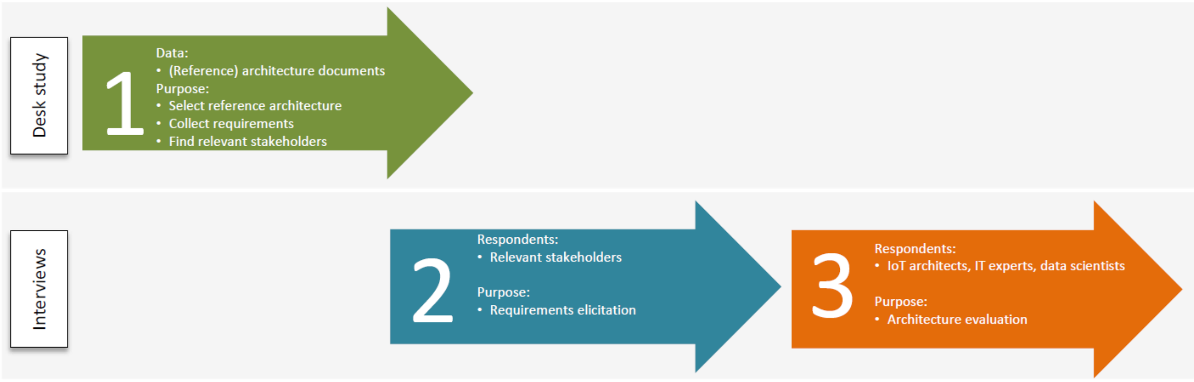



*Figure 7 – Overview of data collection methods in this study*

**Round 1: Requirement process**

The first round of semi-structured interviews consists of both open and closed questions. In the closed questions, stakeholders' opinion on requirements that origin from the desk study will be gathered to prioritized these requirements. For closed questions, it is important that there is a clear objective from the start (Saunders et al., 2009). Because each respondent is asked the same set of questions in a predetermined order, this part of the interview can be seen as a structured interview, a questionnaire (DeVaus & Vaus, 2001). Related requirements are grouped together to prevent that too many questions are asked. An overview of the mapping between interview questions and corresponding requirements is displayed in Appendix D. The questionnaire consists of ten *rating*-questions on a 5-point Likert-type scale – from 'not important' to 'very important' (Boone & Boone, 2012; Brown, 2010). Next to that, there is one *list*-question in which the respondents rank four qualitative requirements of the architecture.

Further, there are also open questions in the interview. These questions have the purpose to collect additional requirements for the IoT solution. The requirements that have been collected are structured using *Volere requirement templates*.

The main advantage of combining a questionnaire with more in-depth interviews is that more insight and understanding is gained in the reasoning behind certain answers (Saunders et al., 2009). This is a common approach for requirement elicitation, where interviews mostly start with predefined questions and additional findings arise during the discussion (Gunda, 2008).

**Round 2: Architecture evaluation**

After the architecture has been developed, a second round of interviews will be conducted. The second round is used to gather the opinion of experts on the proposed architecture. Johannesson & Perjons (2014) argue that interviews are an effective instrument for the gathering of stakeholders' perception about the use and value of the artefact. Again, the interviews will be of a semi-structured nature as this allows to delve deeper in the stakeholders' views.

**Respondent selection**

In total 20 respondents will be interviewed. For the interviews in round 1, respondents are selected based on the stakeholder group to which they belong. Therefore, a stakeholder analysis is needed to identify the stakeholder groups that should to be involved in the design process. After the relevant stakeholders are identified, a representative number of respondents is selected from each of these stakeholder groups. For a small stakeholder, e.g. the *privacy officer*, only one or two respondents are enough, whereas for bigger groups, e.g. *employees*, more respondents are needed to get a representative set of requirements.

For the interviews in round 2, the architecture evaluation, experts on IoT Architectures are interviewed. This are IoT architects, IT experts, and data scientists. The respondents that are selected for the interviews in round 1 (based on the stakeholder analysis in chapter 5) are displayed on the left side in Table 9, whereas the respondents for round 2 are displayed in the right side of this table. There is no overlap between respondents round 1 and round 2.

| Round 1 | |
|---|---|
| **#** | **Stakeholder type** |
| 1 | Employee |
| 2 | Employee |
| 3 | Data scientist |
| 4 | Employee |
| 5 | Employee |
| 6 | Data scientist |
| 7 | Facility manager |
| 8 | Employee |
| 9 | Facility manager |
| 10 | Information systems manager |
| 11 | Information systems manager |
| 12 | Privacy officer |
| 13 | Facility manager |
| 14 | Data scientist |
| 15 | Data scientist |
| 16 | Facility manager |

| Round 2 | |
|---|---|
| **#** | **Stakeholder** |
| 1 | IoT architect |
| 2 | IT expert |
| 3 | Data scientist |
| 4 | IoT architect |

*Table 9 - Type of respondent interviewed for both rounds*

## 3.3. Data analysis

After the data is collected, it needs to be analysed to retrieve valuable information. As the interviews consists of both open and closed questions, data from these questions is analysed in different ways.

### *3.3.1. Closed questions*

Data that has been collected from the closed questions is typified as *quantitative data*. Most answers are collected through a Likert-scale. The answers on such questions fall into the ordinal measurement scale, descriptive statistics that are recommended to use for such answers are the mode, the most frequent response, or the median (Boone & Boone, 2012).

In this part respondents are asked to state the importance of certain statements, statements that are related to requirements that are collected in the desk study. Because the stakeholder groups are varying in size, e.g. more employees are interviewed than privacy officers, the scores on the statements are weighed over the group size: groups that are 'overrepresented' are weighed less. These weights are called *'design weights'* and are calculated by taking the inverse of the inclusion size (European Social Survey, 2014). Thus, first a mean is calculated for *each* stakeholder group separately, the *stakeholder-mean*. After that, the final score is calculated based on the mean of the separate stakeholder-means. The score that is retrieved as a result of this indicates the relative importance of the statement, and thus the relative importance of the corresponding requirement.

To clarify this process, following example: imagine that four employees and two data scientists are interviewed. They are asked to answer the question: *"How important is it that historical information is stored?"* They can answer with a scale of 1 (not important) to 5 (very important). Taking an unweighted mean would result in a final score of 2,7 for this question, whereas a weighted mean would be 3,3. The weighted mean is higher, because the scores of the data scientists have a higher weight.

| **Stakeholder** | **Score** |
|---|---|
| Employee 1 | 1 |
| Employee 2 | 1 |
| Employee 3 | 2 |
| Employee 4 | 2 |
| Data scientist 1 | 5 |
| Data scientist 2 | 5 |
| **Unweighted:** | 2.7 |
| **Weighed:** | 3.3 |

### *3.3.2. Open questions*

Data that has been collected from open questions can be seen as *qualitative data*. This data will be analysed in various steps; first, the interviews are audio-recorded and subsequently transcribed. After that, the data will be analysed by following the analytical procedure *template analysis*. This process has been described by King (2012). A template describes a list of codes that represent themes or categories revealed from data that have been collected (King, 2012; Saunders et al., 2009). For this study this means that stakeholder statements are coded, and that requirements for the system are derived from these codes. Template analysis allows codes to be represented hierarchically, as the goal of this analysis is to find *functional requirements, non-functional requirements*, and *design constraints*, these hierarchical categories will be used as categories for the requirements.

The first step of the analysis is transcribing the audio files. This will be done with the help of qualitative software QDA Miner. After that, statements from the stakeholders will be coded with themes that arise from the data. An overview of statements that are highlighted, together with the sub categories and hierarchical categories is displayed in the coding scheme in Figure 12 in chapter 6.

## 3.4. Data issues

Even though the data collection approach has been described thoroughly and the process will be performed carefully, data issues might always arise during the data collection (Saunders et al., 2009). Potential data issues are described based on the research approach in which they might occur.

#### *3.4.1.Data issues: desk study*

In the desk study, project documents regarding IoT (reference) architectures are needed to analyse. A potential data issue here might be that not enough documents are available, e.g. as development of the reference architecture has not been finished. This potential issue can be mitigated by having a finished reference architecture, as one of the selection criteria for a suitable reference architecture.

Related to that, it might happen that not enough studies can be identified that have applied the reference architecture. Again, this potential issue can be mitigated by having a high availability of previous applications as one of the selection criteria.

#### *3.4.2.Data issues: interviews*

Semi-structured interviews will be used for both the requirement elicitation and the architecture evaluation. The following potential data issues might occur (Gunda, 2008):

1. Lack of technical knowledge from the stakeholder's side
2. Unrealistic requirements, as the system is not understood well by the stakeholders
3. Unclear statements of requirements, these are mostly in general terms, whereas technical terms are needed for the architecture
4. Conflicting requirements among stakeholders

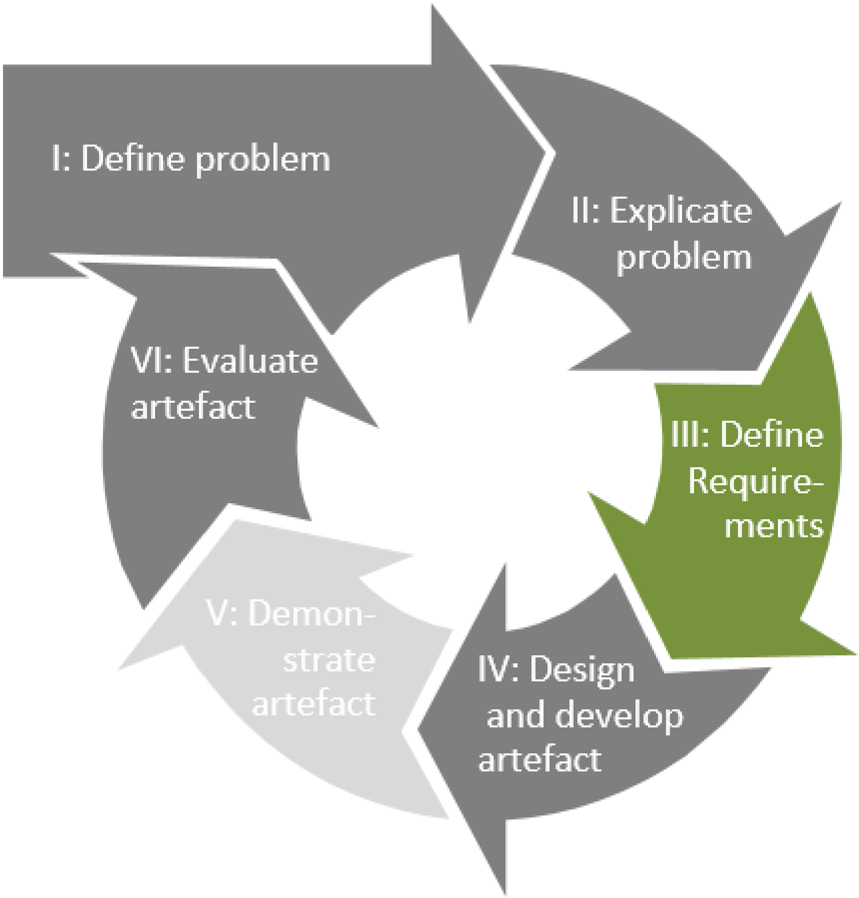
It is crucial to be aware of these potential issues, as measure can be taken to mitigate them. This will be done by describing the envisioned system at the beginning of the interview carefully to the respondents. Also, the scope of the system is explained to the stakeholders as well as what is expected from them.

Another potential issue is that not enough stakeholders available for the interviews, or that respondents are not willing to cooperate. This issue will be mitigated by conducting a comprehensive stakeholder analysis to identify the key parties that are needed. Further, meetings will be planned early on in the process to prevent agenda-issues.

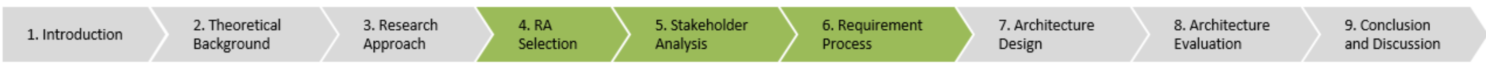
### 3.5.Chapter conclusion

In this chapter the research approach has been described to reach the research objective. Through a case study in The Edge Amsterdam, 'the world's most sustainable building', a general IoT architecture for workspace optimization will be designed and evaluated. This will be done by performing a desk study, and by conducting two rounds of interviews with relevant stakeholders. In total, 20 respondents are interviewed in two rounds – 16 for requirement elicitation and 4 for architecture evaluation. Data from these interviews is analysed in two ways; closed questions are analysed by calculating the *stakeholder-mean*, and open questions are analysed through the analytical procedure *template analysis*.

# Phase III: Define Requirements




This is the third phase of Design Science Framework by Johannesson & Perjons (2014). In this phase, an artefact will be outlined that can address the problem that has been explicated in the previous phase. Requirements for this artefact to be designed will be collected by following the research approach that has been described.




Chapter 4: Reference architecture selection, Chapter 5: Stakeholder analysis, and Chapter 6: Requirement process are part of this phase.

# 4. Reference Architecture Selection

In this chapter, a reference architecture will be selected that will be used as a basis for the workspace optimization IoT architecture to be developed. First, requirements for this reference architecture will be discussed, after which the selected reference architecture will be explicated.

## 4.1. Selection Criteria

In chapter 3 the research objective for this study is derived: *design an IoT architecture for workspace optimization that is based on common grounding and has a clear focus on capabilities for data management.* In the theoretical background in chapter 2 various initiatives for IoT references architectures have been discussed. Knowledge gaps that have been stated in that chapter will be used as *reference architecture selection criteria*, as these knowledge gaps indicate what currently is missing or what is needed. A suitable reference architecture is needed to overcome these gaps. In Table 10 a mapping of the knowledge gaps and selection criteria is presented.

| Knowledge gaps | Selection criteria |
|---|---|
| KG 1: There is a lack of academic research on workspace optimization, a structured design / architecture that can be used to design and implement such a solution is missing | 1. The reference architecture must facilitate that specific use case architectures are derived |
| KG 2: Due to differences in approach of IoT use cases, there is the threat that the IoT devices and solutions remain isolated and cannot communicate with each other effectively, reducing potential for smart cities and smart buildings | 2. The reference architecture must be based on common guidelines and best practices to improve interoperability<br>3. The reference architecture must be scalable; it can be extended |
| KG 3: There is a need for common understanding between stakeholders that are involved in use cases for smart cities and smart buildings | 4. The reference architecture must support architectural views which describe separate aspects of the architecture and can be used for communication purposes |
| KG 4: A clear focus on capabilities for data management is lacking in IoT solutions, whereas this needs to be taken into account from the start, especially when privacy sensitive data is collected. | 5. The reference architecture must have an integration of capabilities for data management. |

*Table 10 – Mapping of knowledge gaps to reference architecture selection criteria*

Next to these requirements, two additional requirements are stated that are not directly related to the knowledge gaps, but more to findings from the problem exploration and potential data issues that are identified in chapter 3.

6. The reference architecture must be developed or sponsored by both agencies and companies
    - Support by *both* agencies and companies is needed to unify development and to prevent that companies force their own standards.
7. The reference architecture must be finished and available, but is still supported
    - A finished reference architecture with several publications indicates that the reference is useful for deriving specific architectures.
8. The reference architecture must be widely supported and validated by practitioners and researchers
    - Wide support the reference architecture is an indication of validity and quality.
    - When use cases that are based on the reference architecture already exist, the reference architecture has potential to be the standard.

The 8 *reference architecture selection criteria* are used to compare the several initiatives for IoT reference architectures that were discussed in chapter 2. The comparison is based on publications of these initiatives, a survey on 'reference architectures for the Internet of Things' by Weyrich & Ebert

(2016), and an analysis of IoT reference architectures by Cavalcante et al. (2015). The findings of this comparison are displayed in Table 11.

| IoT Reference Architecture Initiative | 1. facilitate use cases | 2. common guidelines | 3. scalability | 4. support architectural views | 5. Focus on data management | 6. supported by agencies | 7. finished development | 8. widely supported |
|---|---|---|---|---|---|---|---|---|
| Reference Architecture Model Industrie 4.0 (RAMI 4.0) | ✓ | ✓/✗ | ✓ | ✓ | ✓/✗ | ✓ | ✗ | ✓/✗ |
| Industrial Internet Reference Architecture (IIRA) | ✓ | ✓ | ✓ | ✓ | ✓/✗ | ✓ | ✗ | ✓/✗ |
| Internet of Things – Architecture (IoT-A) | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ |
| Standard for an Architectural Framework for the Internet of Things | ✓ | ✓ | ✓/✗ | ✓ | ✓/✗ | ✓ | ✗ | ✓ |
| Arrowhead Framework | ✓ | ✓ | ✓ | ✗ | ✗ | ✓ | ✗ | ✓/✗ |
| OTA Framework | ✓ | ✓ | ✓/✗ | ✗ | ✓/✗ | ✓ | ✗ | ✓ |
| WSO2 | ✗ | ✓/✗ | ✓ | ✗ | ✓/✗ | ✗ | ✗ | ✗ |

*Table 11 – Comparison of initiatives for IoT reference architectures*

From Table 11 can be inferred that the IoT Architectural Reference Model (IoT-A) is the only IoT reference architecture that has finished development, while being widely supported. These two aspects are important, because enough documentation needs to be available for the design of the architecture, whereas wide support indicates that the reference architecture is perceived as useful. Several EU-funded IoT projects have used IoT-A as a reference architecture, e.g. COSMOS (2017) and FIESTA (2017). Therefore, the IoT-A reference architecture is explored further in the following section.

## 4.2. IoT Architectural Reference Model

The Internet of Things Architectural Reference Model (IoT ARM), IoT-A in short, is developed through a European FP7 project from 2009 to 2013. The main objective of the researchers is to improve interoperability among IoT solutions, which is currently lacking due to the development of solutions with specific challenges in mind (i.e. architectures are designed ad-hoc for solutions). The researchers observed *“vertical and isolated solutions”,* while only a more *“horizontal approach”*, with a *“common technical grounding and common architectural principles could lead to a full fledge Internet of Things”* (IoT-A, 2013:21).

The researchers expect that a common reference model for the IoT domain and the identification of a reference architecture can lead to a significant increase in IoT solutions, as well as faster and more effective development. According to their research, there are two important shortcomings of existing solutions. The first shortcoming is a lack of scalability requirements, in terms of communication between and manageability of devices. The second shortcoming is that current IoT solutions consist of governance models that are not compatible with each other (Carrez et al., 2013).

**Benefits of IoT-A**

IoT-A has numerous benefits according to researchers that contributed to the development. The following benefits mentioned by Bassi et al. (2013) are relevant for this study:

1. It is a cognitive aid that can be used to guide discussions between stakeholders, as it provides a language that can be understood by them and provides a clear overview of the building blocks that are needed for an IoT solution.

2. It establishes a common grounding for the IoT field by defining IoT entities and describing their basic interactions and relationships with each other.
3. It provides a clear pattern that can be used to generate compliant architectures for specific systems. There is a certain degree of automation in the process, which makes designing the system easier. This is done by providing best practices and guidance in the generation of specific use-case architectures.
4. It increases interoperability between IoT solutions significantly, especially when the solution-architectures are based on IoT-A. As the architectures have the same structure and building blocks, discrepancies between the architectures are easily identified. Parts of the architecture that need to be 'connected' can easily be identified. Interoperability is much more difficult to obtain when architectures are not based on common guidelines and design principles (which is the current trend).
5. IoT-A provides the main building blocks for domain-specific architectures in the form of architectural views. These were discussed before in chapter 2.3.2 as being very useful for describing separate but interrelated aspects of architectures. IoT-A adopts the approach of Rozanski & Woods (2011) to describe architectures using views and viewpoints.

IoT-A consists of three deliverables, which together *"can be used for building fully interoperable concrete domain-specific IoT Architectures"* (IoT-A, 2013:37): the IoT Reference Model, IoT Reference Architecture, and Guidelines.

**1. IoT Reference Model**

The IoT Reference Model is the first step in the creation of an architecture, as it describes the concepts and definitions that are important for an IoT architecture in a common language. Figure 8 provides an overview of the IoT Reference Model as defined by the researchers. In this overview the various sub-models and their interaction is displayed.

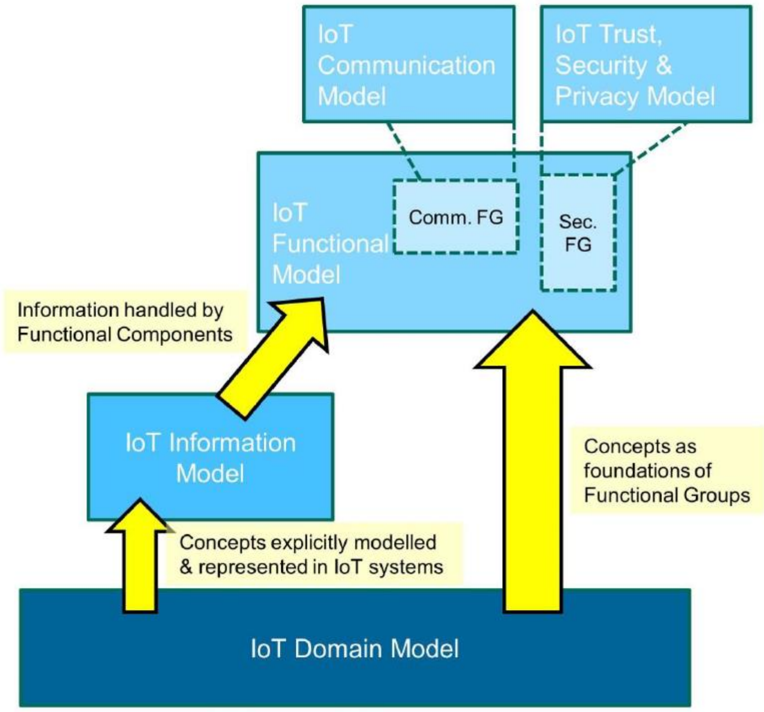



*Figure 8 – Sub-models in the IoT Reference Model* (Carrez et al., 2013)

From Figure 8 can be inferred that the IoT Domain Model is the most important for the Reference Model, The Domain model describes basic concepts such as devices, services and virtual entities, as well as the responsibilities and relationships between these concepts. The need for such a common understanding is argued for several years already by researchers such as Haller (2010) who state that there are many definitions for IoT concepts, and this lack of uniformity hampers scientific discourse.

***1.1 Domain Model***

The Domain Model can be considered as a formal definition of what the IoT domain is, regarding IoT concepts and relationships between those concepts. The concepts are defined on an abstraction level that the concepts are independent of specific technologies and use cases. For example IoT devices are generally stated, without mention of specific techniques (Carrez et al., 2013). The following terms are described IoT-A project documents (Bassi et al., 2013; Bauer et al., 2012; COSMOS, 2017; FIESTA, 2017). Appendix A1 displays an UML representation of the IoT Domain Model.

*User: t*he user is a human or digital artefact (service, application) that interacts with a physical entity. This interaction can be directly (e.g. pressing a button), or indirectly (e.g. by calling a service). In use case architectures, the interaction is characterized by the user goal (for the scope of the model).

*Physical Entities (P-Es): p*hysical entities are objects in the real world that are of interest for the user for the achievement of their goal. Almost everything can be a physical entity, humans, cars, chairs, doors etc. P-Es are represented digitally by virtual entities.

*Virtual Entities (VEs): v*irtual Entities are digital representations of P-Es, examples are e.g. 3D models and database entries. VEs are digital artefacts, and they form the basis of IoT systems. There is a distinction between Active Digital Artefacts (ADA), e.g. running software applications or running services, and Passive Digital Artefacts (PDAs), e.g. database entries. VEs can be instrumented by e.g. sensors, tags and actuators, which are devices. At last, VEs are able to interact with other VEs, e.g. for collaboration (sharing the same goal) or cooperation (getting help from other VE to achieve their own goal).

*Augmented Entities* (AEs)*: a*ugmented Entities are the composition of a VE and the related P-E. They can be explicitly 'connected' through an AE to highlight that the two entities belong together. AEs represent thus both the digital and physical aspect of a 'thing'.

*Devices:* devices bridge digital and physical worlds. There are three basic types of devices; sensors, actuators and tags. Sensors report data or information on the physical entities they monitor, actuators modify the state or properties of these physical entities, whereas tags are used to identify physical entities.

*Resources:* resources are software components that are used to e.g. actuate on physical entities. There is a distinction between on-device resources (e.g. software that is runs locally on the actuator to perform an action), or network resources (e.g. cloud-based databases).

*Services:* services expose resources. For each VE there might be several services that provide different functionalities, which allow for interaction with P-Es. Martin (2012) defines three types of Services, with a varying level of abstraction.

- Resource-level services expose the functionality of a device by accessing its resources. These services refer to a single resource.
- Virtual Entity-level services provide access to information at a virtual-entity level. These services are used to access the VE's status or attributes.
- Integrated services are combinations of the two aforementioned services when combining readings for different sensors (e.g. an empty room might be indicated by light status, motion detection, and reservation data).

### *1.2 Information Model*

The IoT Information Model is developed based on the IoT Domain Model. The IoT Information Model represents the concepts of the IoT Domain Model that are to be explicitly represented and manipulated in the digital world. Relations and attributes of information for virtual entities in an IoT solution are displayed on a conceptual level and can be used to represent information flows throughout the system.

### *1.3 Functional Model*

The IoT Functional Model is a hierarchical model which is used to identify groups of functionalities based on concepts in the IoT Domain Model. The distinction in Functional Groups (FGs) corresponds to the service-oriented approach of IoT. The functional model consists of seven longitudinal FGs, and two transversal FGs: management and security. The transversal FGs provide functionalities that are required by each of the longitudinal FGs. The IoT Functional Model is displayed in Appendix A2.

The following longitudinal FGs are described:
*IoT Process Management:* this FG has the purpose to allow the integration of (business) process management systems with the IoT platform that can be used for experiments with the IoT system. Thus, here the business objects and processes are combined with the world of IoT. This can be used for all kinds of experiments with IoT systems, such as experimenting with new use cases.

*Service Organisation:* this FG acts as a communication hub between several other FGs. This FG links e.g. service requests from the IoT process management FG to basic resources that are needed to perform the process steps. For example; a business process in the *IoT Process Management FG* that needs to involve entities from the *Virtual Entity FG* to determine the temperature in room 123. This is translated to the concrete IoT service (e.g. “sensor service XYZ”). Thus, the *Service Organisation FG* composes and orchestrates services. Service composition is a central concept in the architecture, due to the relatively limited functionality of e.g. sensors, composition combines multiple basic services in order to answer (business) questions at a higher level, e.g. combining a motion sensing service and a pressure sensing service to determine the occupancy of a desk.

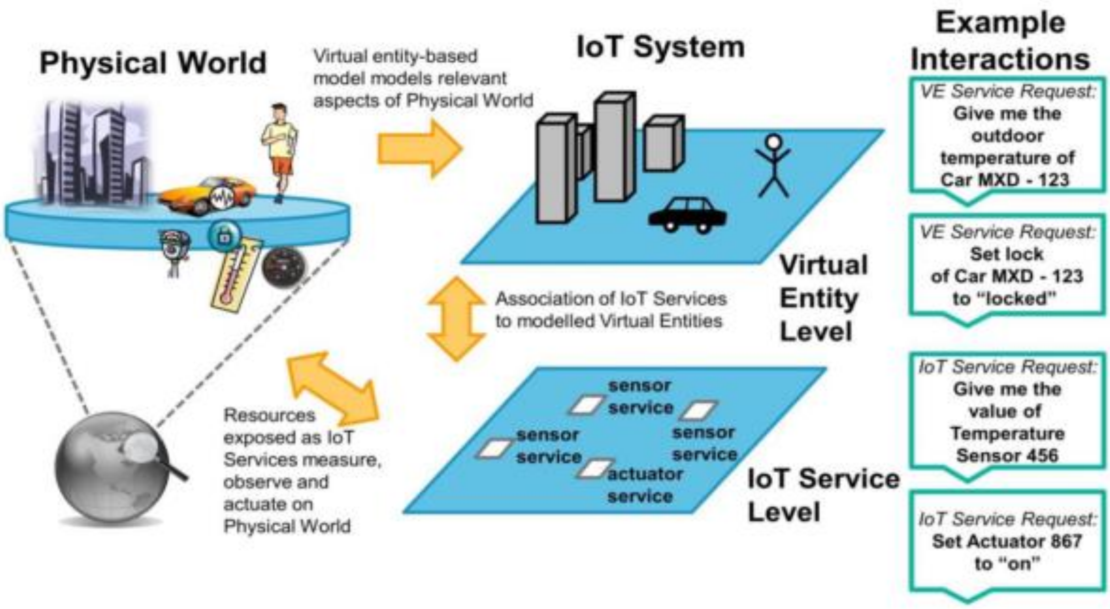



*Figure 9 – IoT-service and Virtual Entity abstraction level* (Bassi et al., 2013)

In Figure 9 is displayed how sensors and actuators in the physical world are represented on the *virtual entity level* and the *IoT service level*. The resources that are used by these sensors and actuators are exposed as IoT services on the IoT service level. In order to facilitate interactions on the virtual entity level, the relation between IoT services and virtual entities needs to be modelled. E.g. when the temperature of car 123 is asked, the corresponding sensor needs to be known.

*Virtual Entity FG*: this FG contains functions for the interaction with the IoT system on basis of the VE level, such as discovering services that allow for the interaction with VEs. Also functionality for managing associations, as well as finding new associations and monitoring their validity.

*IoT Service FG:* this FG contains functions relating to IoT services. These services expose resources like sensors and actuators. Functionalities for discovery, look up, and name resolution of IoT services are described here.

*Communication FG:* this FG abstracts the variety of communication mechanisms that are used for/by IoT devices and provides a common interface to the *IoT service FG* that is simpler for managing high-level information flow. Starting from the top layers of the ISO/OSI model the following aspects are taken into account: data representation, end-to-end path information, addressing issues, network management and device specific features.

*Management FG:* this FG combines the functions that are needed to govern an IoT system and works closely together with the other transversal FG: *Security FG.* The *Management FG* deals with e.g. unexpected events (failing devices, unforeseen usage) and fault handling (detection of potential failures, repairs).

*Security FG:* this transversal FG has the responsibility to ensure security and privacy of IoT-A compliant systems. E.g. ensuring who may access and use the system, and ensuring anonymity.

## 2. IoT Reference Architecture

The IoT Reference Architecture is based on the IoT Reference Model and consists of views and perspectives. For design of IoT systems, the IoT Context View, Functional View, and Physical-Entity View are most important (Bassi et al., 2013).

### *2.1 Architectural views*

Architectural views represent structural parts of the systems. The following are discussed: Functional View, Information View, Physical-Entity View, and Context View.

*Functional View:* the IoT Functional Model forms the basis for the Functional View. The functional view consists of a functional decomposition, in which the Functional Components (FCs) are derived from the Functional Groups (FGs), based on the requirements for the IoT system. A best-practice is to keep as much as possible of these FCs in the final architecture. The Functional View is displayed in Appendix A3.

*Information View:* the Information View is based on the Information Model in which relations and attributes of information for virtual entities in an IoT solution are displayed on a conceptual level. An Information View is mostly designed to show the information flows in an IoT system.

*Physical-Entity View:* the Physical-Entity view gives information about the Physical Entities that are represented in the IoT system. This consists of the following:

- Overview of P-Es, their associated properties
- Overview of devices that are used to bridge the cyber physical world
- How the devices are associated to the P-Es and their location

*Context View:* the Context View originates from Rozanski & Woods (2011) and is used to define the scope of the architecture by describing the relationships, dependencies, and interactions between the system and its environment.

### *2.2 Architectural perspectives*

Architectural perspectives are applied to views in order to design systems that comply with qualities, such as high performance and high security. Perspectives are stated in pairs, because of their commonalities. The following perspectives are mentioned in IoT-A:

*Evolution & interoperability: e*volution and interoperability are closely related. The evolution perspectives is related to changing requirements over time, e.g. due to technological developments and evolving software. The interoperability perspective is very important for IoT, as described in chapter 2, because the system should be able to handle future technologies. IoT-A states that, among others, future needs should be anticipated through discussions with stakeholders, and that a modular architecture should be preferred.

*Performance & scalability:* performance and scalability are closely related as well. With the significant growth of IoT devices, as described in chapter 2, IoT systems need to be scalable. This means that it should be able to cope with e.g. an enormous growth in users, without compromising in performance. IoT-A states that, among others, processes need to be able to be prioritized, partitioning and parallelization should be enabled, and that computational complexity needs to be reduced.

*Trust, security & privacy:* trust in IoT systems is mainly used to refer to a high quality of data regarding data integrity and data freshness. This is closely related to security of an IoT systems, in which a secure communication infrastructure is needed to provide for high levels of trust. Also privacy is important in these aspects, because e.g. sensitive data needs to be handled well to prevent privacy breaches. IoT-A states, among others, that access policies need to be in place, and that cryptographic techniques need to be used for transmission of identifiers.

*Availability & resilience:* availability in IoT systems refers to the uptime of the system and resources that are used by the IoT system. The resilience perspective describes how 'fool proof' the system is. IoT-A states that, among others, 'transactions' need to be logged, back-up resources need to be available, and that there should be a recovery strategy.

**3. Guidelines**

The guidance chapter of IoT-A describes the process of generating concrete architectures, based on the IoT-A building blocks. The requirement generation process is specified, as well as the sequence in which views need to be generated in order to construct a 'full architecture'.

## 4.3. Chapter conclusion

In this chapter IoT-A has been selected as the IoT reference architecture that will be used for the design of the workspace optimization IoT architecture. This has been done by comparing several initiatives for IoT reference architectures, and scoring them on reference architecture selection criteria that have been constructed based on the knowledge gaps.

IoT-A consists of three main parts: the IoT Reference Model, the IoT Reference Architecture, and Guidelines. Figure 10 displays the role of IoT-A in this thesis.

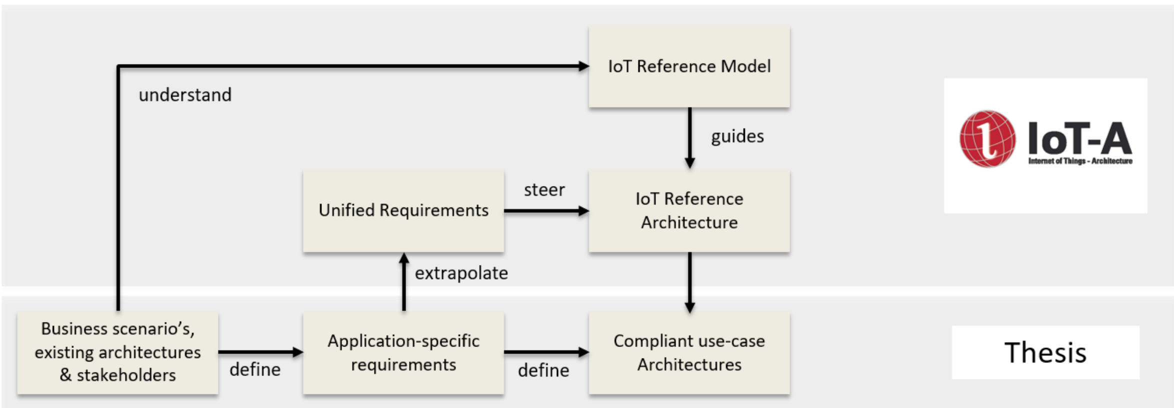



*Figure 10 – Representation of designing compliant architectures, adapted from Bauer et al. (2012:12)*

Based on Figure 10, the following is needed for the generation of a compliant use case architecture: an analysis of business scenario's and stakeholders, and a definition of application specific requirements.

The stakeholder analysis is described in chapter 5, followed by the description of business scenario's and the requirement elicitation process in chapter 6.

# 5. Stakeholder Analysis

In this chapter, the stakeholder analysis, which is needed for the requirements process in the design of the IoT architecture is described. First, stakeholders are identified and analysed by describing their perspective on the problem. After that their resources and dependency is assessed, followed by a power-interest matrix to map the stakeholder-field.

As stated in the previous chapters, one of the main functions of an architecture is to improve the communication between the parties that are involved. Therefore, architectures need to represent their concerns with the system. In the research approach in chapter 3 is described that interviews will be conducted with representatives of important stakeholder groups. In this chapter, these relevant stakeholder groups are identified and analysed. The stakeholder analysis will be performed according to the guidelines of the book *Policy Analysis in Multi-Actor Systems* (Enserink et al., 2010).

## 5.1.Stakeholder analysis process

Systems in which multiple parties are involved that might have different views on a situation, or different (conflicting) objectives are called *multi-actor systems* (Enserink et al., 2010). Typically, such systems are of a socio-technical nature, meaning that the problem has both a social and technical dimension. It is important take both perspectives into account in the design activities, otherwise the project will fail (Bots & Daalen, 2012).

According to Enserink et al. (2010), stakeholder analysis has a specific focus on resources and interdependencies between the parties that are involved. The first step of this analysis is the identification of relevant stakeholders (de Bruijn, ten Heuvelhof, & in 't Veld, 2010; Koppenjan, Bruijn, & Kickert, 1993).

### *5.1.1.Stakeholder identification*

According to Enserink et al. (2010) the actor identification process is mainly performed by thinking *"Who has an interest in or feel the consequences of the issues around which the problem revolves, or the solutions that are being considered?"*. This is called the imperative approach. Another approach is the reputational approach, asking key informants to name relevant stakeholders. These two techniques have been used in a small focus group session in which employees, IoT architects, and facility managers sat together to discuss the use case. Four stakeholder groups have been identified for the scope of this thesis: owners, designers, users, and operators, see Table 12.

| Owner | Designer | User | Operator |
|---|---|---|---|
| Building owner | Information systems manager | Employees | Facility Manager |
| Building tenant | Data Scientist | Visitors | Contractor |
| | Privacy officer | | |

*Table 12 – Relevant stakeholder groups for this study*

### *5.1.2.Problem formulations of stakeholders*

The next step after the stakeholder identification is to explicate their involvement in the project. The stakeholders are analyzed by assessing the following characteristics (Enserink et al., 2010):

- Desired situation: this indicates what the stakeholder desires to realize (or wishes to maintain).
- Situation to prevent: this is a description of a situation that the stakeholders desires to prevent, because the situation is contrasting their interest and objectives.
- Causes: this is what might cause the situation that they want to prevent.

The outcomes of this assessment are displayed in Table 13.

| Stakeholder | | Desired situation | Situation to prevent | Causes |
|---|---|---|---|---|
| **Owner** | Building owner | A well-functioning and safe building with satisfied tenants | The building does not function so well and tenants get dissatisfied | Lack of innovations in the building |
| | Building tenant | A well-functioning and safe building with satisfied users | The building does not function so well and users get dissatisfied | Users get annoyed as they lose time finding vacant desks or each other |
| **Designer** | Information systems manager | Well-designed and well-functioning information system | IoT solutions are siloed, information management is not effective | Lack of IoT vision, lack of good information system design |
| | Data scientist | Various data sources and high-quality data | IoT solutions have no focus on data analysis | Lack of a focus on data analytics in IoT architecture |
| | Privacy officer | Privacy protection of users | User's privacy gets harmed | Personal data is collected that is user identifiable |
| **User** | Employee | A pleasant working environment | An unpleasant working environment | No assigned desks |
| | Visitor | A pleasant working environment | An unpleasant working environment | No available rooms / desks |
| **Operator** | Facility manager | A well-functioning and safe building with satisfied users | The building does not function so well and users get dissatisfied | Users get annoyed as they lose time finding vacant desks or each other |
| | Contractor | A well-functioning building with satisfied users | The building does not function so well and users get dissatisfied | Users get annoyed as they lose time finding vacant desks or each other |

*Table 13 – problem formulation of stakeholders*

#### ***5.1.3. Analyse resources and dependency***

The next step in the stakeholder analysis is to assess the type of resources each stakeholders has, the importance of these resources, their interest in the system, and, based on this all, their criticality to involve in the design process.

- Important resources: the resources a stakeholder has are the formal and informal means that can be used to achieve their objectives (Enserink et al., 2010). According to Kok (1981), numerous types of resources exist, such as information, knowledge/skills, manpower, money, authority/formal power, legitimacy, and position in the network.
- Replaceable: whether a stakeholder is replaceable in the scope of the project is related to the resources they have.
- Dependency: the dependency on a stakeholder is related to the importance of their resources, and whether these resources can be replaced by other resources.
- Critical: critical stakeholders are ones who have a high 'power of realization', or ones who have 'blocking power' – they can hinder the project (Enserink, 1993).

*Building owner:* the building owner has ultimate authority on all decisions regarding the building, they built/bought the building, and can veto what kinds of devices are installed. However, the building owner is mostly not concerned with the day-to-day management of the building, this is mandated to facility management (Swain, 2017). Office buildings are mostly owned by commercial real estate investors, they are mainly concerned with their the value of the building and their ROI (Larson, 2017). Therefore, the building owner is not replaceable, nor dedicated. There is however dependency on them, they have authority.

*Building tenant:* building tenants are clients of building owners. They decide to rent office space in the building and provide a working environment for their employees. Often, multiple tenants are renting the same building, where each tenant is renting a few floors. This happens especially in large buildings

(Siddiqui, 2016). They need to be kept satisfied, otherwise they are able to move out of the building. Therefore, building tenants are dedicated, as they are interested in what happens with the building, but they are also somewhat replaceable. For a workspace optimization solution they are not dependent, thus they are not critical.

*Information systems manager:* information systems managers are working in the IT department of a company. They are responsible for the computer systems within a company, both from the hardware-side and software-side (AGCAS, 2016), and need to be involved when IT-solutions are designed. For a workspace optimization solution they are key, because several sensors (hardware) are needed, as well as servers and networks to enable this. Therefore, they are not replaceable, they are dedicated and dependent on.

*Data scientist:* data scientists works with large amounts of (unstructured) data. They are able to e.g. integrate, process, and analyze that data to gain value from it (Davenport & Patil, 2012). For a workspace optimization solution in which employees are provided with suggestions, advanced analytics are needed, thus data scientists are key. As for information systems managers, they are not replaceable, they are dedicated and dependent on.

*Privacy officer:* privacy officers are focused on all kinds of issues regarding privacy, risks and information. They need to ensure that the company is operating in terms with laws and regulation and mitigate all kinds of risks regarding information management (Kayworth, Brocato, & Whitten, 2005). The privacy officer can kill initiatives if they are not complying with law and regulations, therefore it is important that they are involved in the design of a workspace optimization solution, as personal data is collected on employees. Therefore, they are not replaceable, but they are dependent on and dedicated.

*Employee: e*mployees are the main users of the envisioned system, they are provided suggestions for workspaces. Therefore, it is important that they are involved in the system design, otherwise important considerations from this stakeholder group might be overseen. Employees are expected to use the system when it improves their working experience. When their working experience is not improved or when they have a negative perception of the system, they can ignore the suggestions, or can even try to obfuscate the system if they don't want to use it. Therefore they are dependent on, as well as dedicated.

*Visitor:* visitors are visiting the office building, either once or more frequently. As they can be numerous and are not directly involved in the workspace optimization solution, they are not dependent or, nor are they dedicated.

*Facility manager:* facility managers are concerned with the management of the building, which can be very broad, from design of the office setup, to contracting of e.g. a cleaning company (Swain, 2017). They have the authority on what kind of devices are installed in the building. Therefore, they cannot be replaced. They are dependent, and they are dedicated as well.

*Contractor:* contractors are contracted by facility management to perform certain tasks in the building, such as cleaning or providing (small) repairs on workspaces. Since the potential group of contracts is big, they are replaceable. They are not dependent on, nor dedicated.

The outcomes of this assessment is summarized in Table 14.

| Stakeholders | Important resources | Replaceable | Dependency | Dedicated | Critical |
|---|---|---|---|---|---|
| Building owner | - Authority on all decisions regarding the building<br>- Determines what devices are installed | No | Yes | No | Yes |
| Building tenant | - Position in the network, the tenant pays the owner and provides a working environment | Yes | No | Yes | No |
| Information systems manager | - Knowledge / skills on the design of information systems | No | Yes | Yes | Yes |
| Data scientist | - Knowledge / skills on managing IoT data and getting value out of it | No | Yes | Yes | Yes |
| Privacy officer | - Legitimacy, the PO is employed by the tenant to ensure that the employee's privacy is protected | No | Yes | Yes | Yes |
| Employee | - Position in the network, they are the users of the system. | No | Yes | Yes | Yes |
| Visitor | - No important resources | Yes | No | No | No |
| Facility manager | - Authority on what devices are installed<br>- Authority on building management | No | Yes | Yes | Yes |
| Contractor | - No important resources, they are contracted to perform work in the building (e.g. cleaning) | Yes | No | No | No |

*Table 14 – analysis on criticality of stakeholders*

#### *5.1.4.Power-Interest matrix*

The findings in the previous two steps can be used to generate a 'power-interest matrix', or 'stakeholder map' to visualize which actors are the most important for the project. In this matrix, stakeholders are mapped based on their 'level of interest' in the system, and their 'power'. Four groups are distinguished: crowd, subjects, context setters, and key players. For the design process in this study, the key players are most critical to involve. The Power-Interest matrix is displayed in Figure 11.

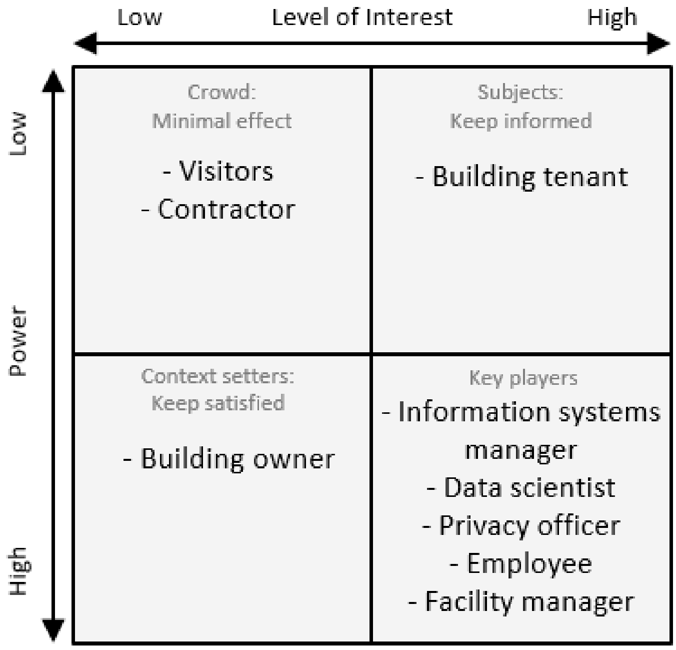



*Figure 11 – Power-interest matrix of the stakeholder analysis*

## 5.2. Chapter Conclusion

From the stakeholder analysis in this chapter can be concluded that there are nine relevant stakeholders involved in this project. However, not all stakeholders are equally important. The *information systems manager*, *data scientist*, *employees*, *privacy officer*, and *facility manager* are the key players; they have both a high level of interest and power. Therefore, they need to be involved in the design of the IoT architecture to ensure that the project has sufficient support. *Building owners* and *building tenants* are also important, as they are high in power; they need to be kept satisfied. *Employees* are key players as they are the main users of the system. *Visitors* and *contractors* are not directly important for this solution, thus they are seen as 'crowd' and don't need to be involved in the design process.

# 6. Requirement Process

In this chapter, the business goals and the requirement process, which is needed for the design of the architecture, will be described.

The requirement process is an important part of the architecture design in IoT-A, because in this step the stakeholders are involved and their concerns are collected (Carrez et al., 2013). This process step is preceded by the description of business goals, which describes the scope of the system and how users envision the system. The business goals are needed to guide the requirement process. Both the stakeholder analysis, which is described in chapter 5, and description of business goals are used as input for the requirement process.

Therefore, the business goals will be describe first, followed by a discussion and explanation of the requirement process. The requirement process is structured according to the requirement elicitation process as described by Sommerville (2006). As stated before, an adapted version of the *Volere requirement templates*, will be used to structure the requirements.

Sommerville (2006) describes the following activities in a requirement process:

1. *Gathering requirements:* discovering new requirements by involving stakeholders in the process.
2. *Classifying requirements:* organizing requirements gathered from different sources.
3. *Analysing requirements:* understanding requirements, finding commonalities among them, and finding requirements that conflict the business goals or each other.
4. *Prioritizing requirements:* discovering priorities among requirements through interaction with stakeholders.

## 6.1. Business goals

The first step in the generation of an IoT-A compliant architecture is the description of business goals (Carrez et al., 2013).

> **IoT-A:** The business goal is the starting point of architectures. In this step, the scope of the system is defined, as well as short description of how the system is envisaged (Carrez et al., 2013).

Findings from chapter 2, in which *workspace optimization* is defined and explained are used as input for the definition of business goals, as well as a focus group session with people working on IoT systems and users. Employees, IoT architects, and facility managers, sat together and discussed the scope for the workspace optimization solution in this project. In particular three main use cases were discussed during this session: *get workspace suggestions, find vacant desks/rooms,* and *find colleagues*.

> **Theory recap:** Workspace optimization is defined as measuring, monitoring and predicting building occupancy through IoT devices, and using this information to optimize workspaces.

As a result of this process, the business goal for this IoT system is described as follows:
*The targeted use cases of this architecture is workspace optimization in smart buildings. The core idea of such a system is that employees are provided with suggestions for a suitable workspace for them on their mobile device (smartphone application). Employees are also able to locate vacant desks and meeting rooms in the building through this application, as well as the location of their colleagues. After employees have located a desk, sensors register that this desk is assigned to an employee. This solution optimizes the use of workspaces in the building and is expected to improve the working experience of employees.*

In short, the scope is as follows:

- Users access the system and see suggestions for desks through an application
- The system provides an overview of vacant desks and meeting rooms
- The system can be used to locate colleagues in the building

Thus predicting building occupancy, as stated in the definition of workspace optimization in this study, is not in the scope of the solution. Instead the system predicts *where* an employee wants to sit in the building –suggestions are provided.

## 6.2. Gathering requirements

The first step of the requirement process is gathering requirements. As described in chapter 3, requirements will be collected in this study through a desk study and through interviews.

*Desk Study*

One of the main deliverables of the IoT-A project is a list of 184 Unified Requirements (UNIs); a set of generalized requirements that have been extrapolated from numerous application-specific requirements that have been collected in previous projects. In the desk study, IoT-A project documents are studied to find suitable UNIs, in order to ensure that this study builds upon the already established best practices. First, each UNI is analysed and rated on their applicability for a workspace optimization solution. Next to that, the description of the UNIs, which is in generalized terms, is adapted to fit the workspace optimization solution. In total, 30 UNIs are found to be suitable for the workspace optimization solution, they are displayed in Appendix D1.

*Interviews*

Next to the UNIs, additional requirements are collected through interviews with relevant stakeholders. By asking the stakeholders questions about the system, their ideas are gathered. The interview protocol that has been used for this process is displayed in Appendix C1. As the stakeholders' view on the system consists of implicit requirements, their statements need to be 'translated' into requirements. This process is performed in various steps, as described in chapter 3. The analytical procedure *template analysis*, which has been popularized by King (2012), is used for this. In this procedure statements from the stakeholders are coded with themes that can are either predefined or arise from arise from the data. IoT-A's architectural perspectives (evolution & interoperability, security & privacy, availability & resilience, and performance & scalability), are used as predefined themes. Next to that, additional themes that become apparent are introduced. At last, the codes are translated into requirements. See Figure 12 for the codebook that has been used for the data analysis of the requirement elicitation process.

## 6.3. Classifying requirements

The next step in the requirement process is to classify the requirements that have been collected through the interviews. IoT-A classifies requirements with the following types:

- Functional requirements: describe what the architecture has to do
- Non-functional requirements: properties that the functions must have
    - Trust, privacy & security
    - Evolution & Interoperability
    - Availability & Resilience
    - Performance & Scalability
- Design constraints: restrictions on design (e.g. use existing setup of devices)

The requirements that have been collected through interviews are classified among the same requirement types. An extensive overview of statements from respondents and the corresponding requirement type is displayed in the first part of Appendix C2, whereas Table 15 provides a summary of the collected requirements, including the requirement type.

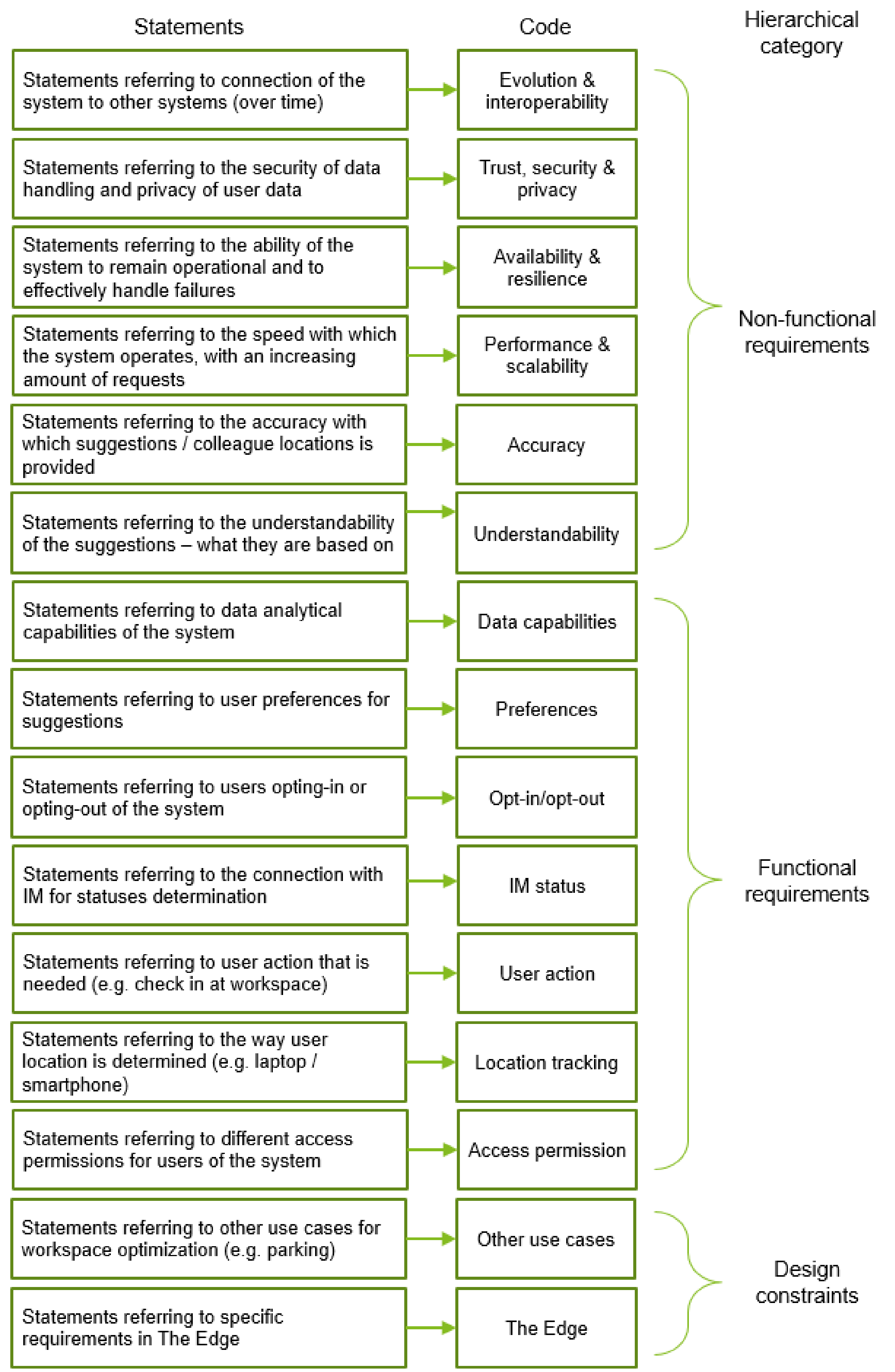



*Figure 12 – Codebook requirement process*

| Req.ID | Requirement | Requirement type |
|---|---|---|
| 1. | The system enables employees to disable tracking (opt-out) | Functional |
| 2. | The system needs employees' approval to start tracking them (opt-in) | Functional |
| 3. | The system is interoperable with other data sources (IM + Calendar) | Design Constraint |
| 4. | The system is able to find IoT devices automatically | Functional |
| 5. | The system determines the u employee's location based on the location of their laptop | Functional |
| 6. | The system determines the employee's location based on the location of their smartphone | Functional |
| 7. | The systems collects and stores no user identifiable data | Functional |
| 8. | The system collects and stores user identifiable data | Functional |
| 9. | The system needs to have a high accuracy of suggestions | Non-functional |
| 10. | The system needs to be able to work in real-time | Functional |
| 11. | The systems needs to be easy to use and easy to understand | Non-functional |
| 12. | The system allows employees to provide their preference for a workspace | Functional |
| 13. | The system needs to be updated with changes in requirements and technologies | Non-functional |
| 14. | The system supports other use cases that are added | Design constraint |
| 15. | The system supports specific constraints of the tenant | Design constraint |
| 16. | The system supports various user permissions for the system | Functional |

*Table 15 – Overview of requirements collected through interviews and their corresponding requirement type*

## 6.4. Analysing requirements

The next step is to analyse the requirements by describing the stakeholders' opinion about the envisioned system, and by assessing conflicts between requirements.

### *6.4.1. Stakeholder opinion*

Stakeholders' opinion about the system is explained by providing example quotes from the stakeholders, as well as the 'Req.ID' that corresponds to this opinion. In the analysis below, each quote contains a reference to the interview in which it was stated, and a Req.ID when applicable, e.g.'#3' indicates that the quote is stated by respondent 3, whereas 'Req.ID 3' indicates that it corresponds to requirement 3 in Table 15. An extensive overview of quotes and corresponding requirement is provided in Appendix C2.

**Employees**

Through interviews with employees, the main users of the envisioned workspace optimization solution, the following becomes clear. First of all, employees are generally enthusiastic about a workspace optimization solution, especially on busy working days. In particular the use case to find vacant desks is welcomed by the employees: *"I think it is really handy to on busy moments, if your preferred place is occupied" (#5)*. The use case to find the location of colleagues is considered less important, but is still welcomed – again, especially on busy days: *"I think it is really handy to sit nearby your colleagues" (#5)* (Req.ID 8). Employees are also suggesting future use cases that are related to this: *"I can also imagine that this system is helpful for finding empty places in the canteen, or even in the parking garage"* (#8) (Red.ID 14).

The main concern of employees is, as expected, their privacy. They want to ensure that their personal data is handled correctly, and that they know on beforehand what kind of data is collected on them, and what this data is being used for: *"Communication is very important as well, users need to know how the system works and what kind of data is collected on them"* (#4) (Req.ID 11). Some employees state that they want to be able to (temporarily) opt-out: *"It is important that I can (temporarily) turn of that my location can be found"* (#1) (Req.ID 1). Others state that opt-in is a better alternative: *"I think that the advantages are not bigger than the privacy infringement. It might help if I opt-in for the moment that I want to share data"* (#10) (Req.ID 2). Interestingly, one facility manager who has experience with the provision of apps to employee's states that privacy is less of an issue than you would expect, especially for younger employees: *"We previously had a perfect picture in which employees needed to check in. This was not being used, but not due to privacy, our generation does not care about privacy that much, it becomes less important"* (#13).

Another important finding is that most employees prefer that their location is determined by tracking the location of their laptop: *"The laptop needs to be used, because your laptop is at the place where you work"* (#2), instead of tracking the location of their smartphone: *"I think it is better to determine the user's location via their laptop instead of their phone, because this infringes the privacy less. When I go to the bathroom I take my phone with me, and people don't need to know when/how long I am away"* (#1) (Req.ID 5). However, there are also employees who believe that the smartphone is more representative for the location: *"It can also be good to determine the location based on their smartphone – it often happens that I go to another floor for a coffee"* (#4) (Req.ID 6).

Also, employees want to have input for the suggestions they are provided with: *"It would be nice if I get a notification of where my team is sitting, to have a user profile in which I can give in preferences, like working in a quiet place"* (#8) (Req.ID 12). The suggestions can also be improved more by connecting other data sources, such as the current IM system or the employee's agenda: *"I think it is always easy, of course we also use Skype here, so you can easily just ask where they are. If someone is in a call, then it is easy to track their location. So it is handy if you see their status already"* (#5) (Req.ID 3). These additional data sources can also prevent that someone is disturbed when he's busy: *"Their Skype status shows if they are available. If someone is busy I won't approach him"* (#8).

**Data scientist**
Through interviews with data scientists the following becomes clear. First of all, in order to be able to provide employees with useful suggestions, it is important that there is a real-time overview of currently occupied workspaces. Also historical data is important to store, in order to derive useful 'clusters': *"Ideally, you have a real-time overview of current occupation, but also historical data to e.g. create zones"* (#6) (Req.ID 10). In order to allow employees' preferences for suggestions, e.g. working in a quiet area, each workspace need to be labeled on beforehand as well. If this is not done, accuracy will be low: *"the algorithms might have a hard time"* (#6) (Req.ID 9). The importance of real-time data is also supported by facility management: *"From a facility management perspective it is important to understand the real-time occupation"* (#13).

Further, in order to ensure that the system works fast, there should be relatively powerful server on which the model runs. However, there can be an efficiency gain by not 'running the model' ad-hoc (when the employee asks for a suggestion), but by creating the clusters of an employee's preferred areas and colleagues e.g. once per week or month. When the employee asks for a suggestion, a simple 'read'-action is performed, which is much more efficient than running the model each time (#3).

**Information systems manager**
Through interviews with information systems managers the following becomes clear. First of all, privacy concerns are raised, because they are aware that collecting and storing user identifiable data has certain constraints related to them. One manager argues that perhaps you can select that your location is shared for a few minutes only: *"I think that the advantages are not bigger than the privacy infringement. It might help if they opt-in for the moment that they want to share data"* (#10) (Req.ID 2, 7, 8). However, tracking the location of an employees' laptop, which is a good indication of the desk the employee is working at, seems much easier to get approved (#10) (Req.ID 5).

On important consideration from the IT department is how critical the software is for the functioning of the building. When, for example, no one is able to occupy a desk without the software, the software becomes 'mission critical', which means that it should have a very high priority inside the IT department, meaning that it needs much more resources than needed for regular use, and that maintenance needs to happen more frequently (#10). Another consideration is about the way the application is accessed;

when this is only available via a smartphone, people without a smartphone are unable to use the system. So *"you need to have a console in a shared space that people can use to find a workspace or their colleague"* (#10).

Further, it is argued that understandability is always an important issue with IT solutions, if people don't understand or find it difficult to use, you might have a problem: *"I think that people in our department would use such an app easily, but this does not have to be the case, it should be easy to use"* (#11) (Req.ID 11).

**Facility manager**

Through interviews with facility managers the following becomes clear. First, facility management expects that such a solution does increases the value of the building, because the building can be used more efficiently – there is less waste (#7). Next to that, by collecting data on the individual workspaces, facility management gets better insight in the way the workspace is used, resulting in various benefits, such as decreased maintenance costs: *"you can save costs regarding cleaning, catering, climate, energy, lightning"* (#9).

However, there are a few important considerations that need to be taken into account. The building in the case, The Edge, has specific restrictions from facility management regarding the floors that some departments can use. Departments working with extremely confidential data and documents, e.g. M&A, are working only on a certain floor. The system needs to take this constraint into account; *"this department has activities that cannot be merged with others. This are things that you need to take into account if you provide suggestions"* (#7) (Req.ID 15). Also, facility management needs to be able to decide that some desks are defect, these desks should then not be offered as a suggested workspace. Thus, different access permission roles for the system need to exist (#9) (Req.ID 16).

Further, due to the experience facility management has with the provision of apps to employees, they have learned that people are annoyed when they need to take some action themselves: *"We encounter that when we offer apps, people are annoyed if they have to take some action themselves, like logging in"* (#13) (Req.ID 4), and when the systems are not working as expected: *"It is important that the system is easy-to-use, up-to-date, and accurate. If the system says that a room is available, it should indeed be available. There is nothing more frustrating than an occupied room when you expect it to be vacant"* (#13) (Req.ID 9, 11, 13).

**Privacy officer**

Through interviews with privacy officers the following becomes clear. Obviously, privacy of users is an important aspect of a workspace optimization system, as employees' location is being tracked. The privacy officer states that this solution can *only* work when employees explicitly agree with the fact that their location is being tracked – it *should* be opt-in: *"privacy law simply states that you cannot process user identifiable data when this is not needed. There should be a business necessity if you want to oblige this. The only option you have is to let employees opt-in voluntarily"* (#12) (Req.ID 2).

Next to that, the privacy offer raises concerns that this solution can be used as a 'personal tracking system', meaning that each movement of an individual is being tracked: *"I don't want that my manager checks how many hours I have been in the office [this would be a reason not to share my data]"* (#12). Therefore, communication on what kind of data is collected, and what this data is being used for is extremely important. Not only is to persuade employees to share their data, instead this needed by law (Req.ID 11).

### *6.4.2. Conflicting requirements*

From section 6.4.1 can be derived that the stakeholders' opinion have resulted in 16 additional requirements that are collected for the workspace optimization solution. However, several of these requirements are found to be conflicting with each other – this is due to the fact that the stakeholders are varying in opinion. The requirements from the desk study and interviews that are found to be conflicting are displayed in Table 16.

| Req.ID | Requirement | Conflicting |
|---|---|---|
| 1 | The system enables employees to disable tracking (opt-out) | 2 |
| 2 | The system needs employees' approval to start tracking them (opt-in) | 1 |
| 5 | The system determines the u employee's location based on the location of their laptop | 6 |
| 6 | The system determines the employee's location based on the location of their smartphone | 5 |
| 7 | The systems collects and stores no user identifiable data | 8, bus. goal, UNI.041 |
| 8 | The system collects and stores user identifiable data | 7 |
| UNI.041 | The system provides historical information about the physical entity | 7 |

*Table 16 – Overview of conflicting requirements collected through interviews*

These conflicting requirements will be handled by prioritizing them in section 6.5. The relative priority of two conflicting requirements is discussed in that section.

## 6.5. Prioritizing requirements

The last step in the requirement process is the prioritization of requirements. In the closed questions, respondents were provided with statements and asked to rate these statements on their importance. The statements are related to UNIs – the mapping between statement and UNIs is provided in Appendix D. The process of data analysis for the closed questions is explained in chapter 3 – weighted means are used to compensate for overrepresentation of certain stakeholder groups. Findings of the data analysis are displayed in Appendix C2.

Requirements that were collected through open questions are prioritized in the following way; each requirement is individually discussed, and the priority is indicated by the frequency in which the requirement emerged, and by certain stakeholders that indicate a priority (e.g. a requirement that is related to something in the law has a higher priority than a requirement that is based on a stakeholder's perception). Based on the relative difference, priorities of requirements are stated as *high, medium* or *low*. This process is also described and performed in Appendix C2.

In this section, the conflicting requirements in Table 16 are briefly discussed. The priority-rating for these requirements is presented in Table 17.

| Req.ID | Requirement | Priority |
|---|---|---|
| 1 | The system enables employees to disable tracking (opt-out) | High |
| 2 | The system needs employees' approval to start tracking them (opt-in) | High |
| 5 | The system determines the u employee's location based on the location of their laptop | High |
| 6 | The system determines the employee's location based on the location of their smartphone | Low |
| 7 | The systems collects and stores no user identifiable data | Low |
| 8 | The system collects and stores user identifiable data | High |
| UNI.041 | The system provides historical information about the physical entity | Medium |

*Table 17 – Prioritization of conflicting requirements*

Requirement 1 and 2 are conflicting, as they describe a different way in which users start using the system. Req. 1 states that all users are being tracked, *unless* they opt-out, whereas req. 2 states that users are not being tracked, *unless* they opt-in. Through the interviews became clear employees cannot be tracked automatically (by law), so an opt-in is a must. They must also be able to stop tracking, so an opt-out should also be available. Therefore, both requirements are rated as **high**.

Requirement 5 and 6 are also conflicting, as they describe a different way in which employees are being tracked throughout the building. Req. 5 states that this happens through the MAC-address of their laptop, whereas req. 6 states that their smartphone should be used. From the interviews became clear that most respondents prefer to be tracked through their laptop, as this indicates their ‘real’ working place. Further, they also take their smartphone when they go to the bathroom, they don’t want to be tracked then. Thus, req. 5 is rated as **high**, whereas req. 6 is rated as **low**.

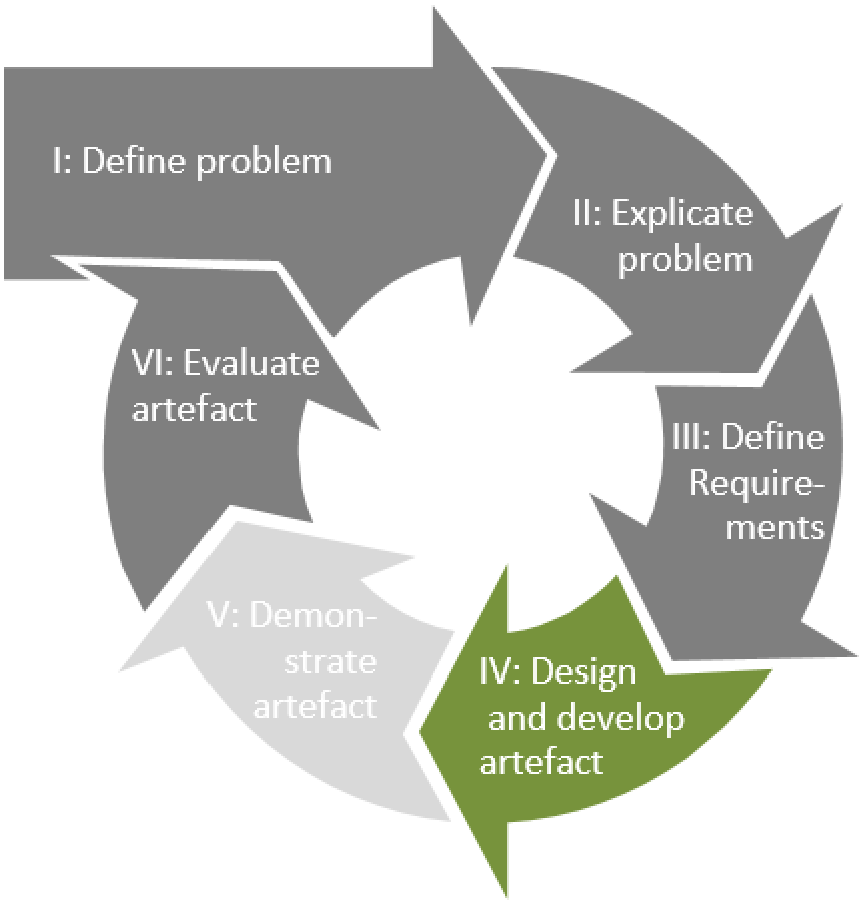
Requirements 8 and UNI.041 are conflicting with req. 7, as the former two state that user identifiable data is collected and stored, whereas the latter states that this does not happen. In the use case is described that user identifiable data is needed to improve workspace suggestions, as well as allow employees to find the locations of their colleagues in the building, therefore req. 8 is rated as **high**. Further, in section 2.3.2 is thoroughly described that data management is important, especially when sensitive data is collected. As user identifiable data is only collected when employees opt-in, and design choices will be made to preserve user privacy, e.g. by storing it for only a short time period, req. 7 is rated as **low**. At last, UNI.041 is rated as **medium**, based on quantitative analysis on closed questions that were presented to the respondents.

The complete list of requirements, including both the UNIs and collected requirements is displayed in Appendix D.

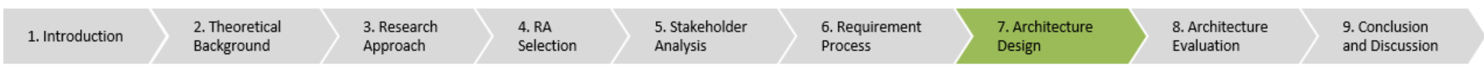
## 6.6. Chapter Conclusion

From the requirement process, the following can be concluded. First of all, the various stakeholders have, as expected, various requirements for the system. Interestingly, there are also requirements that are shared by multiple stakeholders, this indicates the strength of these requirements, as discussed in the prioritization step. In total, there are 30 unified requirements selected for this system, and 16 additional requirements collected through interviews. However, of these requirements, only 26 are rated as having a high priority.

# Phase IV: Design and develop artefact




This is the fourth phase of Design Science Framework by Johannesson & Perjons (2014). In this phase an artefact is created that fulfils the requirements that have been collected in the previous phase.




Chapter 7: Architecture design is part of this phase.

# 7. Architecture Design

In this chapter, the design process is thoroughly explained, and the proposed architectural views are provided.

The architecture generation process has been inspired by assessing project deliverables of projects that have applied IoT-A successfully (COSMOS, 2017; FIESTA, 2017). Interestingly, the sequence of the design-process and architectural is not always the same, this is depends, on e.g. the specific use case and on the goal of the architecture. However, from the project documents can be inferred that the Physical-Entity View, Context View, Information View, and Functional View are most important, therefore they are also developed for this use case.

1. Create Physical-Entity View
2. Create Context View
3. Create Information View
4. Create Functional View

Next to that, two Process View will be designed that clarify (1) how the system is used, and (2) how the four architectural views mentioned above can be used to design and implement a *solution architecture* (i.e. an architecture that can be used for the implementation)

Throughout the description of design choices in the architectural views will be referred to requirements that are collected from stakeholders by stating the requirement ID. A full overview of these requirements is presented in Appendix D.

## 7.1. Physical-Entity View

Based on the system description and the scope of the IoT solution, and the requirements that have been collected in chapter 6, the Physical-Entity View can be defined. In this section, several studies that discuss occupancy estimation techniques (as already described in the theoretical background, chapter 2) will be used to reason why certain physical entities or devices have been included in this view.

**Theory recap:** The Physical-Entity view gives information about the Physical Entities that are represented in the IoT system. This consists of the following:

- Overview of P-Es, their associated properties
- Overview of devices that are used to bridge the cyber physical world
- How the devices are associated to the P-Es and their location

For the workspace optimization solution, the following is stated:

*Physical-Entities:*

Physical-Entities are the real world objects that are of interest for the system. The description of business goals indicates that the following is needed for this system.

- **Desks:** desk are the workplace of employees. They are spread throughout the building and can be equipped with sensors to determine vacancy (R. Greenfield, 2017).
- **Devices:** laptops are carried around by employees in the building. Their location can be used as a proxy of the location of the owner (the employee). This location can be determined through several ways, e.g. WiFi triangulation (Balaji et al., 2013; Melfi et al., 2011).
- **Meeting rooms:** this are rooms in the building that can be used by employees. Several sensors can be installed in these rooms to measure occupancy (Melfi et al., 2011; Yang, Li, Becerik-Gerber, & Orosz, 2012b).

*Virtual entities:*
Virtual entities are the digital representations of the physical entities, e.g. database entries. Each virtual entity consists of several attributes.

- **DeskVE:** these virtual entities represent desks. They consists of the following attributes:
  - DeskID – unique ID for each desk
  - Floor – floor on which the desk is located
  - Space – building space in which the desk is located
  - State – occupancy status of the desk
- **DeviceVE:** these virtual entities represent employees. They consists of the following attributes:
  - EmployeeID – unique ID for each employee
  - Floor – floor on which the laptop is located
  - Space – space on which the laptop is located
  - MAC – MAC address of the laptop
  - AccessPoint – accesspoint to which the laptop is connected
- **MeetingRoomVE:** these virtual entities represent meeting rooms. They consists of the following attributes:
  - RoomID – unique ID for each room
  - Floor – floor on which the room is located
  - Space – building space in which the room is located
  - State – occupancy status of the room

*Devices:*
Devices are used to bridge the physical and digital world, e.g. sensors, actuators and tags. For desk occupancy, sensors exist that can be placed under the desk and measure whether a person is using the desk in real-time (R. Greenfield, 2017; OccupEye, 2017). Further, several studies describe how WiFi logs can be used to infer the location of devices that are connected to WiFi Access Point by determining the relative signal-strength, WiFi triangulation (Balaji et al., 2013; Melfi et al., 2011). At last, motion sensors are already successfully used to determine whether a room is occupied. Currently this is mainly done for energy savings purposes (Melfi et al., 2011). Unfortunately, inferring the number of occupants in the room is not possible with these sensors. As this is out of scope for this solution, as described in the business goals, a motion sensor suffices.

- **DeskSensor:** is attached to desks and collect data on the occupancy status of the desk.
- **APSensor:** Access Points collect data on their 'clients', such as the MAC address, which can be used to infer the owner of the device.
- **MotionSensor:** is placed in meeting rooms to measure movement (i.e. occupancy) in the room.

The Physical-Entity view provides an architectural overview of these categories, see Figure 13 for an UML-Class representation of this view.

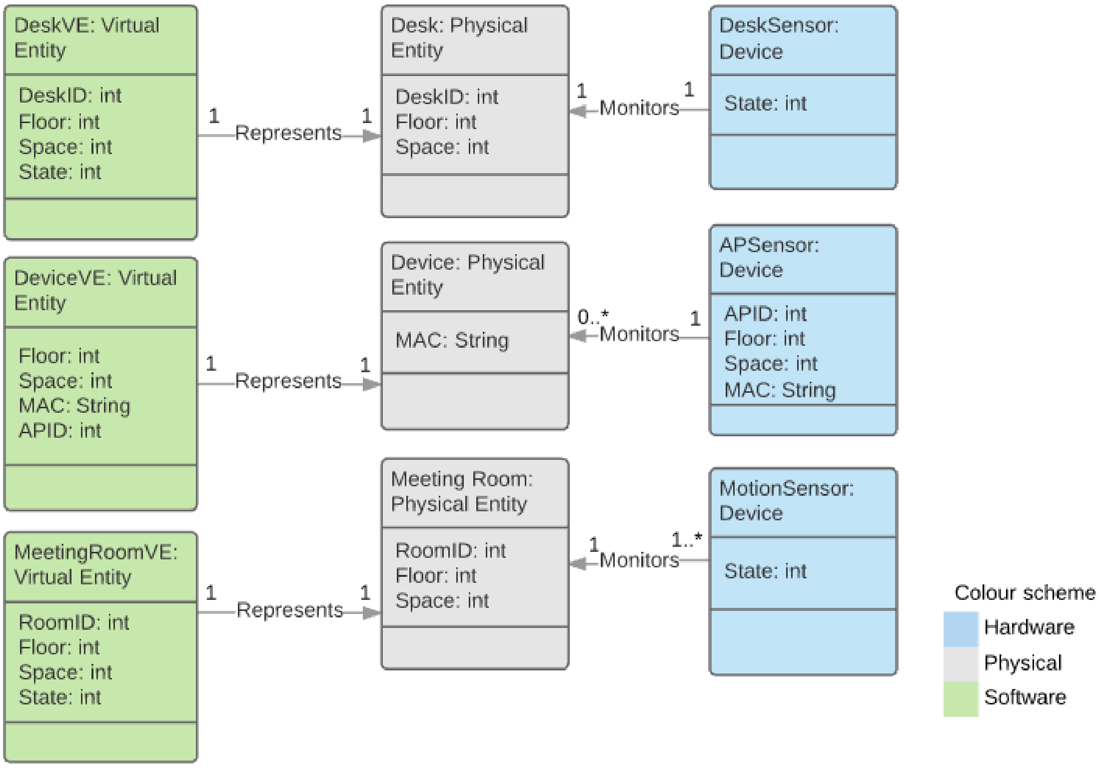



*Figure 13 – Physical-Entity view for the workspace optimization solution*

## 7.2. Context View

The next step in the generation of an IoT-A compliant architecture is the creation of the Context View. In the Context View the system scope is explained further by describing the system responsibilities, and the identity of external entities, interfaces, services, and data used (Woods & Rozanski, 2009). Since the system scope is already defined and described in the business goals, there is some overlap expected between the two sections. Further, the Context View can be kept rather descriptive to clarify the solution in non-technical terms, as the IoT Domain Model adds the IoT-specific context, which is presented in the Information View (Bassi et al., 2013).

> **IoT-A:** The Context View originates from Rozanski & Woods (2011) and is used to define the scope of the architecture by describing the relationships, dependencies, and interactions between the system and its environment in a concrete overview

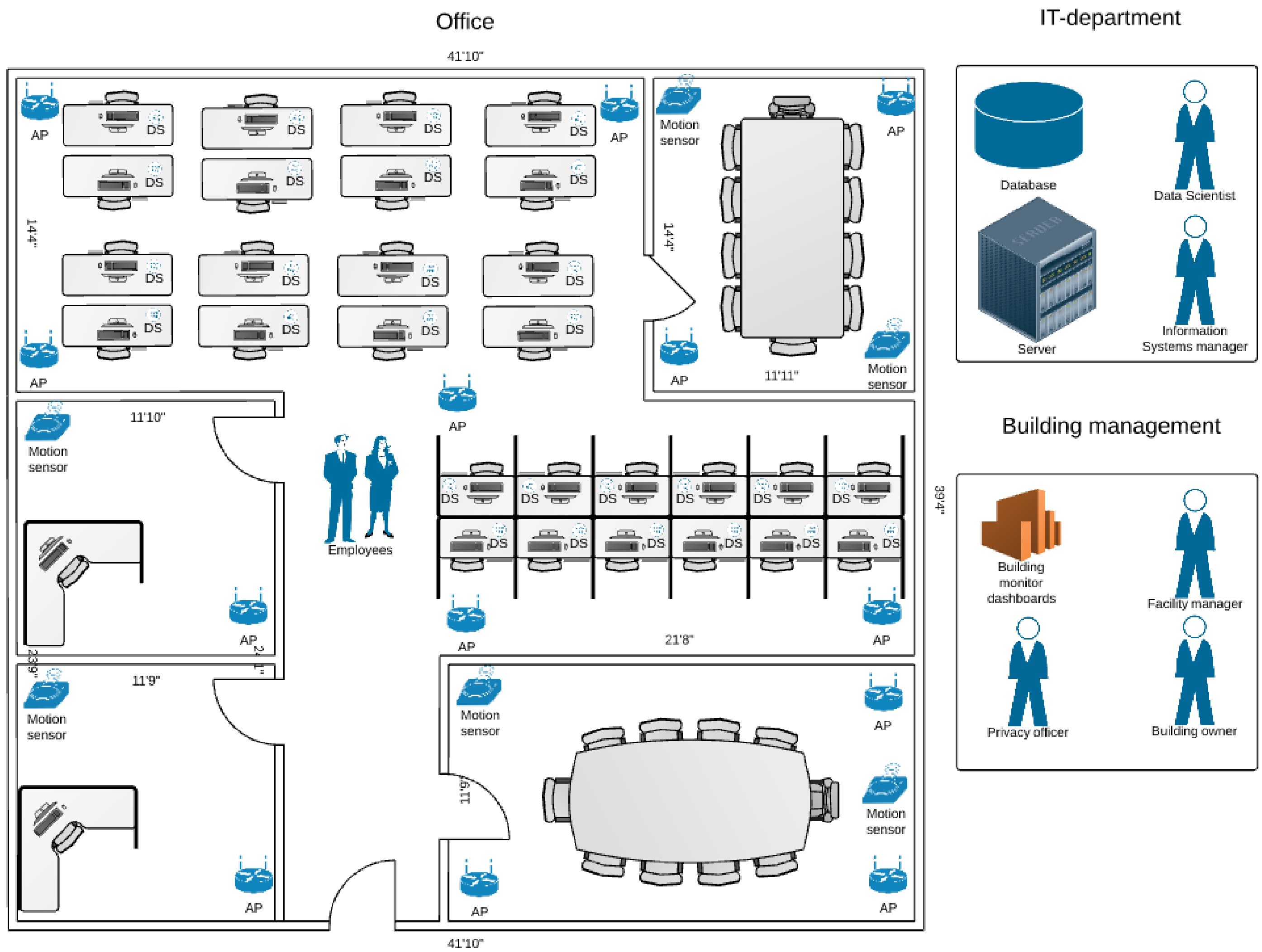



*Figure 14 – Context View of the workspace optimization solution*

In Figure 14 an overview is provided of a simplified office floor plan setup that consists of 28 desks in an open floor plan, and four meeting/working rooms. Added to the floor plan are the sensors as described in the Physical-Entity view: desk sensors on each desk (DS), motion sensors in meeting/working rooms, and WiFi Access points throughout the entire floor. Users of the system are displayed as well, as they are defined in the stakeholder analysis. Also two separate departments are visible that are not directly placed on the office floor; a building management department that monitors the usage of the building, and an IT department that houses the necessary resources and services that are exposed.

## 7.3. Information View

The next step is to derive the Information View, based on the IoT Domain Model. Input for this View is provided in the previous sections; the business goals, Physical-Entity View, and the Context View. The Information View is presented in Figure 15, it can be seen as an extension of the P-E View, with a more elaborate overview of the system.

> **IoT-A:** The Information View uses the IoT Domain Model to enrich the standard context view with IoT-specific context and more details on the inner working of the envisioned system (Bassi et al., 2013).

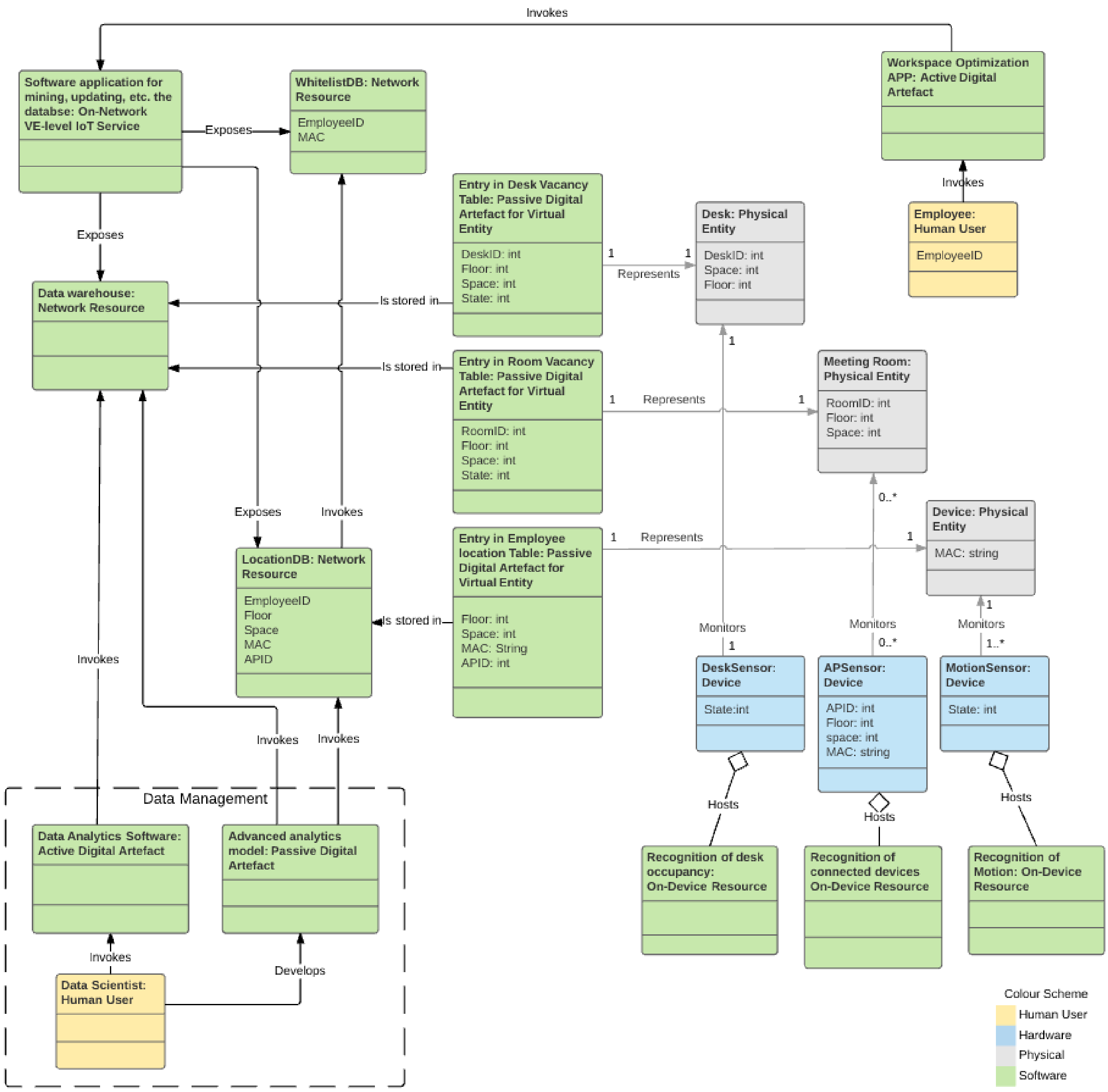



*Figure 15 – Information View*

As can be seen in this View, the following design choices have been made (see also Figure 16). As described in chapter 2.3.2, choices regarding capabilities for data management are important to cope with challenges regarding *integration & storage,* and *processing & analytics*, in particular with privacy constraints in mind, as privacy & security was found to be the most important quality for the IoT system during the requirement process.

First, an important requirement for the system is that employees need to *opt-in* before their location can be tracked (Req.ID 2). This is fulfilled by allowing employees to voluntarily sign up for the system in the app on their company smartphone. Employees that opt-in are added to an encrypted database that stores a unique identifier for each employee, and the MAC-address of their device: *WhitelistDB*. Further, data from the WiFi Access Points (highly sensitive data) is stored in a separate database that is only accessible by a few authorized persons: *LocationDB* (Req.ID 16). Data is only stored if there is a match with records in the Whitelist DB, i.e. when the employee did opt-in (UNI.502). This is done to ensure that no data is stored of employees that did not register.

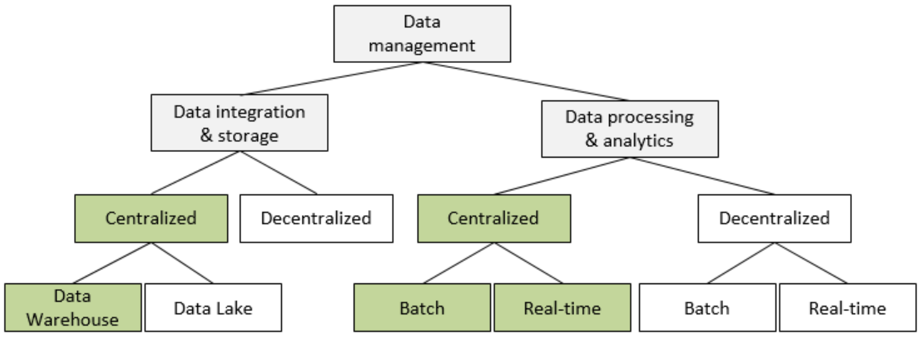


*Figure 16 – Applied design choices for data capabilities in the IoT system, with a focus on preserving privacy*

Data that is collected by the *DeskSensors* and *MotionSensors* are integrated and stored in a centralized location, a data warehouse. As described before, a data warehouse integrates and stores data that fits a schema: data is cleaned before it is stored, it contains minimal noise and is mostly structured (Brennan & Bakken, 2015; Furlow, 2001). Data processing & analytics are also performed in a centralized way, through a combination of both batch processing and real-time processing. Batch processing is used to perform analytics on the *location DB*, as well as on the data in the data warehouse. Analytics on the *LocationDB* are mainly performed to derive 'clusters' of employees that often sit together, these insights are stored in the data warehouse and are used to suggest workspaces.

After each week, data in the *LocationDB* is flushed; as the analytics are already performed, there is no need to store this data any longer (Abu-Elkheir et al., 2013)(Req.ID 7/8). Analytics on the data warehouse are performed when employees request suggestions for workspaces, these suggestions are retrieved by combining data sources (e.g. desk that are vacant *and* nearby the employee's cluster of colleagues). Analytics on the data warehouse are also used for the creation of e.g. a dashboard that provides usage statistics to facility management.

The employee accesses the system through a smartphone application. By sending a request (e.g. retrieve a workspace suggestion) the suitable database is queried, and the response is sent back to the employee. Facility management has an application as well, this is used to manage the workspaces (e.g. 'turn off' desks that need to be fixed).

A more elaborate description of the functionalities in the IoT system is provided in the functional view.

## 7.4. Functional View

The following and final step in the architecture design is to derive the functional view for the workspace optimization IoT Architecture. The Functional View provides an abstract and high-level description of the system components that are needed. Creating a Functional View is fundamental in the development of (IoT-A compliant) Architectures, as it provides a complete description of the system, which is not possible with the foregoing architectural views. The Functional View displays how the requirements that are collected are applied, and is useful for communication purposes. The Functional View is derived by applying the requirements that have been collected (through the desk study and the interviews) on the Functional Model, which is described in chapter 4.

> **IoT-A:** "The functional Model is an abstract framework for understanding the main *functionality groups (FGs)* and their interactions. This framework defines the common semantics of the main functionalities and will be used for the development of IoT-A compliant Functional Views" (Carrez et al., 2013:133)

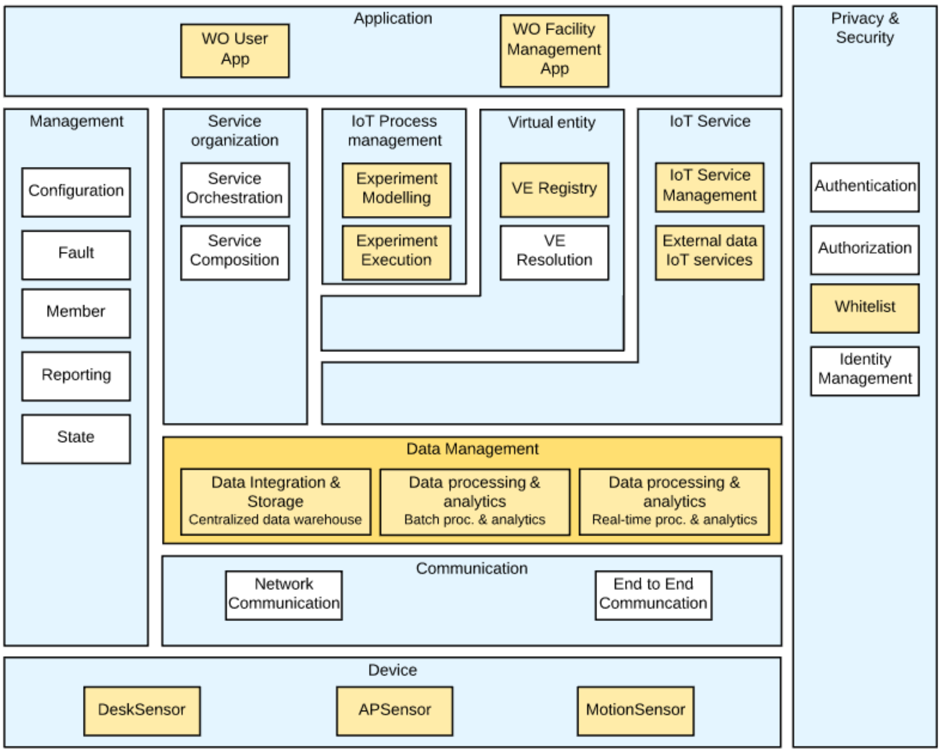



*Figure 17 – Functional View of the proposed architecture for workspace optimization. Blue and white 'boxes' represent Functional Groups (FGs) and Functional Components (FCs) respectively (IoT-A default). Yellow 'boxes' represent FGs and FCs that are added/adapted for the Workspace Optimization solution*

The Functional View consists of a functional decomposition, in which the Functional Components (FCs) are derived from the Functional Groups (FGs), based on the requirements for the IoT solution. A best-practice is to keep as much as possible of these FCs in the final architecture. For the development of the Functional View, FCs other studies that have applied IoT-A have been studied (COSMOS, 2017; FIESTA, 2017).
IoT-A's Functional Model and Functional View are displayed in Appendix A2 and A3 respectively. The Functional View of the proposed architecture for workspace optimization is displayed in Figure 17. The FGs and FCs that are displayed in this view are explained and motivated by presenting the requirements that specify the need for them. Note that in Figure 17 the FGs and FCs that are different from the ones prescribed by IoT-A are coloured yellow.

### *7.4.1. Application FG*

The Application FG consists of the following FCs: *Workspace Optimization APP, WO Facility Management APP.* This is conform the following business goals/requirements:

| ID | Description |
|---|---|
| Business goal | The system is accessed via a smartphone application |
| 1. | The system enables employees to disable tracking (opt-out) |
| 2. | The system needs employees' approval to start tracking them (opt-in) |
| 12. | The system allows employees to provide their preference for a workspace |
| 16. | The system supports various user permissions for the system |

**IoT-A:** The Application FG describes how the IoT solution is presented to users of the system (COSMOS, 2017).

**WO User App**
This application presents the application front-end to the user. Users can use this application to sign up (opt-in) for the system, or sign off (opt-in) whenever they want. Further, this application retrieves a set of needed configuration information from the end-user that is used to suggest workspaces, e.g. preferences for a workspace can be provided as input by the employee.

**WO Facility Management App**
This application presents the application front-end and retrieves user input from facility management users. This application presents insights regarding workspaces in the building, and is used to manage workspaces: e.g. a facility manager can declare a specific desk to be unavailable due to a broken screen, or even close a whole floor when this is needed. ‘Regular’ users are not authorized to use this app.

### *7.4.2.IoT Process Management FG*

The IoT Process Management FG consists of the following FCs: *Experiment Modelling FC,* and *Experiment Execution FC.* This is conform the following requirements:

| ID | Description |
|---|---|
| 13. | The system needs to be updated with changes in requirements and technologies |
| 14. | The system supports other use cases that are added |
| 16. | The system supports various user permissions for the system |

> **IoT-A:** The IoT Process Management FG relates the integration of traditional process management systems with the IoT ARM. The aim is to provide functional components and interfaces to augment traditional business processes with IoT characteristics (Carrez et al., 2013)

**Experiment Modelling FC**
For workspace optimization, this component is used to model experiments by persons with access rights to use the collected data for this purpose, e.g. data scientists. Models can be developed to experiment with new use cases or new data sources.

**Experiment Execution FC**
This component is responsible for the execution of experiments that have been modelled in the *Experiment Modelling FC*. VE services and IoT services that are needed in the experiments are invoked from this component.

### *7.4.3.Service Organisation FG*

The Service Organisation FG consists of the following FCs: *Service Orchestration FC,* and *Service Composition FC.* This is conform the following requirements:

| ID | Description |
|---|---|
| UNI.010 | The devices/services in the system are able to collaborate for a certain task |
| UNI.047 | The system ensures interoperability between objects or between applications |
| UNI.065 | The system provides reliable services |
| UNI.252 | The service organization shall provide feedback within a reasonable amount of time. |

| | |
|---|---|
| UNI.102 | The system takes external computing resources into account, e.g. 'the cloud'. |
| 16 | The system supports various user permissions for the system |

**IoT-A:** “The Service Organisation FG is the central FG that acts as a communication hub between several other FGs. IoT-A uses services as a primary concept of communication, therefore the Service Organisation FG is used for composing and orchestrating services” (Carrez et al., 2013:169).

**Service Orchestration FC**

This component resolves the IoT service that is suitable to fulfil service requests coming from either the *Experiment Execution FC* or from Users. Its function is to orchestrate the suitable IoT services that are capable of handling the requests. If needed, temporary resources will be set up to retrieve and store intermediate results that can be used by the *Service Composition FC* if this is needed for the system performance (Carrez et al., 2013). Examples of an IoT service are ‘show vacant desks’, or ‘suggest workspace’.

**Service Composition FC**

This component works closely together with the *Service Orchestration FC*. This function of this component is to combine IoT services to create services with extended functionality, if needed by e.g. Experiments (Carrez et al., 2013). The services are chosen based on their availability and the access rights of the users.

### *7.4.4.Virtual Entity FG*

The Virtual Entity FG consists of the following FCs: *VE Registry FC,* and *VE Resolution FC*. This is conform the following requirements:

| ID | Description |
|---|---|
| UNI.016 | The system supports physical entity location tracking (logical location) |
| UNI.050 | The system supports mobile physical entities |
| UNI.099 | The system guarantees correctness of resolutions |
| UNI.414 | The system enables the dynamic discovery of virtual entities and their services |
| UNI.423 | When performing discovery, resolution or lookup, the system must respect any aspect of privacy, including the possibility to retrieve information about or related to people. In addition some services should be accessible in an anonymous way, while others might require an explicit authentication or authorization of the user. |
| UNI.502 | The system prevents a device from being activated without the consent of the owner. |
| 2. | The system needs employees’ approval to start tracking them (opt-in) |
| 4. | The system is able to find IoT devices automatically |
| 5. | The system determines the employee’s location based on the location of their laptop |

**IoT-A:** “The Virtual Entity FG contains functions that are used for interaction with VEs, as well as functionalities for managing existing associations, finding new associations and monitoring their validity” (Carrez et al., 2013:171)

VE’s in the context of workspace optimization are virtual representations of desks, meeting rooms, and (the location of) laptops (which is assumed to represent the location of the device owner).

**VE Registry FC**
This component is used for the creation and management of VE’s and their associations with Physical Entities, IoT resources, and IoT Services (FIESTA, 2017). An example is the association between physical desks/meeting rooms and their digital representation, the VE. VE’s can only be resolved if they are registered first. Unknown devices (e.g. devices of employees who did not opt-in) are not associated with physical entities, resources, or IoT Services, and are thus not tracked.

VE Resolution FC
This component is used to retrieve associations between VE’s and IoT Services. This is thus the discovery of new and mostly dynamic associations between VE’s and associated services (Carrez et al., 2013). As an example: employees who carry their laptops (digitally represented as VE’s) around the building are constantly connecting to different access points, thus they are constantly creating new associations between VE’s and IoT services.

#### *7.4.5.IoT Service FG*

The IoT Service FG consists of the following FCs: *IoT Services, Raw-data Pre-processing, Analytics, Inference & Prediction,* and *External Data IoT Services*
This is conform the following requirements:

| ID | Description |
|---|---|
| Business goal | Users get suggestions for workspaces, or get an overview of vacant desks, meeting rooms, and the location of their colleagues |
| UNI.005 | The system supports event-based, periodic and/or autonomous communication |
| UNI.041 | The system provides historical information about the physical entity |
| 3. | The system is interoperable with other data sources (IM + Calendar) |
| 10. | The system needs to be able to work in real-time |
| 15. | The system supports specific constraints by the tenant |
| 16 | The system supports various user permissions for the system |

> **IoT-A:** “The IoT Service FG contains functionalities for discovery, look-up and name resolution of IoT services” (Carrez et al., 2013:174).

IoT Services for the workspace optimization solution are the following: *suggest workspaces*, *find vacant desks/meeting rooms*, and *find your colleague*. Further, there is also an IoT Service that is specific for facility management: *Manage workspaces*. This can be used to manage workspace and create reports regarding trends in occupation.

**IoT Service Management FC**
This component is used for the creation and management of IoT Services. The association between the IoT Services and network resources (e.g. databases) that are needed for the fulfilment of these IoT Service are managed by this component. IoT Services can be created by authorized users (e.g. data scientist) when new use cases for the system are developed. IoT Services are used to return the information from resources (e.g. provide user with information on vacant desks that is stored in the data warehouse). This can happen event-based (on user request) or in fixed intervals (e.g. each 5 minutes).

**External Data IoT Services FC**

External data sources that are added to the IoT system (over time) are either associated with existing IoT Services, or part of new IoT Services. For example, when employees' calendars are added as a new data source, this can be part of a new IoT Service in which automatically meeting rooms are found and added to the calendar. The existing IoT Service for the suggestion of workspaces can then also use this new IoT Service to improve the accuracy of suggestions.

### *7.4.6.Data Management FG*

The Data Management FG is not prescribed by the IoT-A reference architecture. The need and importance of integrating capabilities for data management is described in chapter 2.3.2. Design choices that have been made regarding data management are argued in chapter 7.4, where the Information View is described. This FG consists of the following components: *Data Integration & Storage FC,* and *Data Processing & Analytics FC*. This is conform the following requirements:

| ID | Description |
|---|---|
| Business goal | Users get suggestions for workspaces, or get an overview of vacant desks, meeting rooms, and the location of their colleagues |
| UNI.005 | The system supports event-based, periodic and/or autonomous communication |
| UNI.018 | The system supports capabilities for data management (integration & storage, processing & analytics) |
| UNI.041 | The system provides historical information about the physical entity |
| UNI.606 | The system makes the traceability of digital activities impossible |
| 9. | The system needs to have a high accuracy of suggestions |
| 10. | The system needs to be able to work in real-time |

**Data Integration & Storage FC**

This component is used for functionalities regarding data integration and storage. As described before, a centralized solution is most fitting for this system; a data warehouse. This is complemented with two separate databases for privacy purposes. Only data from the sensors is stored, as well as results from analytics that are performed for the suggestion of workspaces. Storage of personal data is no longer needed after the analytics have been performed, therefore this data is deleted after one week.

**Data Processing & Analytics FC**

This component is used for functionalities regarding data processing and analytics. As described before, this system supports both batch processing and analytics, as well as real-time processing and analytics, as both are needed for the various IoT Services. Users are able to rate the suggestions that are provided to them, these ratings are incorporated in the training of the model. It is expected that this improves the accuracy of suggestions.

### *7.4.7.Privacy & Security FG*

The Security FG, as defined in the IoT-A Reference Architecture is renamed as Privacy & Security FG to explicitly express the importance of privacy in this IoT system. This FG consists of the following FCs: *Authentication, Authorization, Whitelist,* and *Identity Management*

This is conform the following requirements:

| ID | Description |
|---|---|
| UNI.062 | The system provides trusted and secure communication and information management |
| UNI.067 | The system provides different access permissions to information |
| UNI.410 | The system restricts who can update and delete Digital Entity history |
| UNI.411 | The system offers a unique identification of clients requesting data via the discovery / lookup services |

| | |
|---|---|
| UNI.423 | When performing discovery, resolution or lookup, the system must respect any aspect of privacy, including the possibility to retrieve information about or related to people. In addition some services should be accessible in an anonymous way, while others might require an explicit authentication or authorization of the user. |
| UNI.503 | The system makes it be possible to change the owner of a device |
| UNI.504 | The system prevents tracking of the identifier of the device by unauthorized entities. |
| UNI.606 | The system makes the traceability of digital activities impossible |
| 1. | The system enables employees to disable tracking (opt-out) |
| 2. | The system needs employees' approval to start tracking them (opt-in) |
| 11. | The system needs to be easy to use and easy to understand |
| 16. | The system supports various user permissions for the system |

**IoT-A:** The Management FG combines all functionalities that are needed to govern an IoT system. This consists of managing users and use cases and to identify, isolate, and correct faults (Carrez et al., 2013:133)

**Authentication**
This component is used for User authentication. It checks the credentials that a user provides and, if valid, proceeds to the *Authorization FC* to check their access rights. In companies, this is often linked to the companies' authentication method, this ensures that employees can access the system with their current company-account, which makes the system easier to use.

**Authorization FC**
This component is used for the management of access control policies. These control policies can be called whenever access to a restricted resource is requested. The *IoT Service Resolution FC* can call this component to check whether it is allowed to perform a lookup on the requested resource (COSMOS, 2017). For workspace optimization, this is especially relevant for the tracking of individuals' device location. An opt-in is needed, this is stored in the *Whitelist FC*. The *Authorization FC* is used to add, update or delete the access policies.

**Whitelist FC**
This component registers employees that have agreed to have their location tracked throughout the building. A unique identifier is stored, together with an identifier of the employee's device. This component is used by the *Authorization FC* to provide access to restricted resources.

**Identity Management FC**
This component addresses privacy concerns by issuing unique identifiers for users that agreed to opt-in to the system. These identifiers are consequently used to store user preferences for the system, e.g. a preference to sit nearby colleagues or in a quiet workspace.

### *7.4.8.Communication FG*

The FCs for the Communication FG are generally independent of specific IoT use cases, therefore the FCs as prescribed by IoT-A will be applied unchanged in this architecture. This are the following FCs: *Network Communication*, and *End to end Communication*. This is conform the following requirements:

| ID | Description |
|---|---|
| UNI.012 | The system is able to handle interference between IoT devices (avoidance and detection) |
| UNI.506 | The system supports communication across devices by aid of standardized communication interfaces. |
| 13. | The system needs to be updated with changes in requirements and technologies |

**IoT-A:** "The communication FG is used to abstract the communication mechanisms used by the Devices. Communication technologies used between Applications and other FGs is out of scope for this FG as these are considered to be typical Internet technologies" (COSMOS, 2017:63).

**Network Communication FC**
This component *"takes care of enabling communication between networks through Locations (addressing) and ID Resolution. The FC includes routing, which enables linking different network address spaces. Moreover different network technologies can be converged through network protocol translations"* (Carrez et al., 2013:175).

**End to End Communication FC**
*"This component takes care of the whole end-to-end communication abstraction, meaning that it takes care of reliable transfer, transport and translation functionalities, proxies/gateways support and of tuning configuration parameters when the communication crosses different networking environments"* (Carrez et al., 2013:175).

### *7.4.9. Management FG*

As with the Communication FG, the FCs for the Management FG are mostly independent of specific IoT use cases, therefore the FCs as prescribed by IoT-A will be applied unchanged in this architecture. This are the following FCs: *Configuration, Fault, Member, Reporting,* and *State*. This is conform the following requirements:

| ID | Description |
|---|---|
| UNI.066 | The system provides integrity validation of virtual entities, devices, resources, and services |
| UNI.093 | The system shall be extensible for future technologies. |
| UNI.714 | The system management shall pay attention to device constraints such as energy and memory |
| UNI.715 | The system performs data collection on its current state |
| 1. | The system needs to be updated with changes in requirements and technologies |
| 2. | The system supports other use cases that are added |
| 15. | The system supports specific constraints of the tenant |

**IoT-A:** The Management FG combines all functionalities that are needed to govern an IoT system. This consists of managing users and use cases and to identify, isolate, and correct faults (Carrez et al., 2013:133)

**Configuration FC**
This component *"is responsible for initializing the system configuration such as gathering and storing configuration from FC's and Devices. It is also responsible for tracking configuration changes and planning for future extension of the system"* (Carrez et al., 2013:179). The configuration is either retrieved from history (e.g. last used settings by a user) or it is set during initialization (e.g. when a user puts in different preferences).

**Fault FC**
This component is used to *"identify, isolate, correct and log faults that occur in the IoT system. When a fault occurs, the respective functional component notifies the Fault FC"* (Carrez et al., 2013:180). An example of action that can be taken automatically when a certain fault occurs is to use external resources (e.g. the cloud to keep the system available).

**Member FC**
This component *"is responsible for the management of the membership and associated information of any relevant entity (FG, FC, VE, IoT Service, Device, Application, User) to an IoT system"* (Carrez et al., 2013:180). Information (capabilities, ownership, rules rights) about entities is mostly stored in a database. This FC works closely together with the *Authorization FC* and *Identity Management FC*.

**Reporting FC**
This component *"can be seen as an overlay for the other Management FCs. It distils information provided by them. One of the any conceivable reporting goals is to determine the efficiency of the current system"* (Carrez et al., 2013:180-181). This component seems thus very interesting for the Information Systems Manager, as this stakeholder is concerned with the (technical) functioning of the system and its components.

**State FC**
This component *"monitors and predicts the state of the IoT system. For a ready diagnostic of the system, as required by Fault FC, the past, current, and predicted (future) state of the system are provided"* (Carrez et al., 2013:181).

### *7.4.1.Device FG*

At last, the Device FG is displayed. In this FG the sensors that are deployed in the IoT system are described. A description of the sensors is already provided in the Physical-Entity View, they are added to the Functional View for the purpose of completeness.

## 7.5. Process Views

Next to the four architectural views, two process views are designed to provide a better understanding of the system, regarding its usage and regarding its implementation.

### *7.5.1. System Usage*

This process view is used to provide a simple overview of how the system is used by employees. This process is modelled using the BPMN 2.0 modelling language (Allweyer, 2011) and displayed in Figure 18.

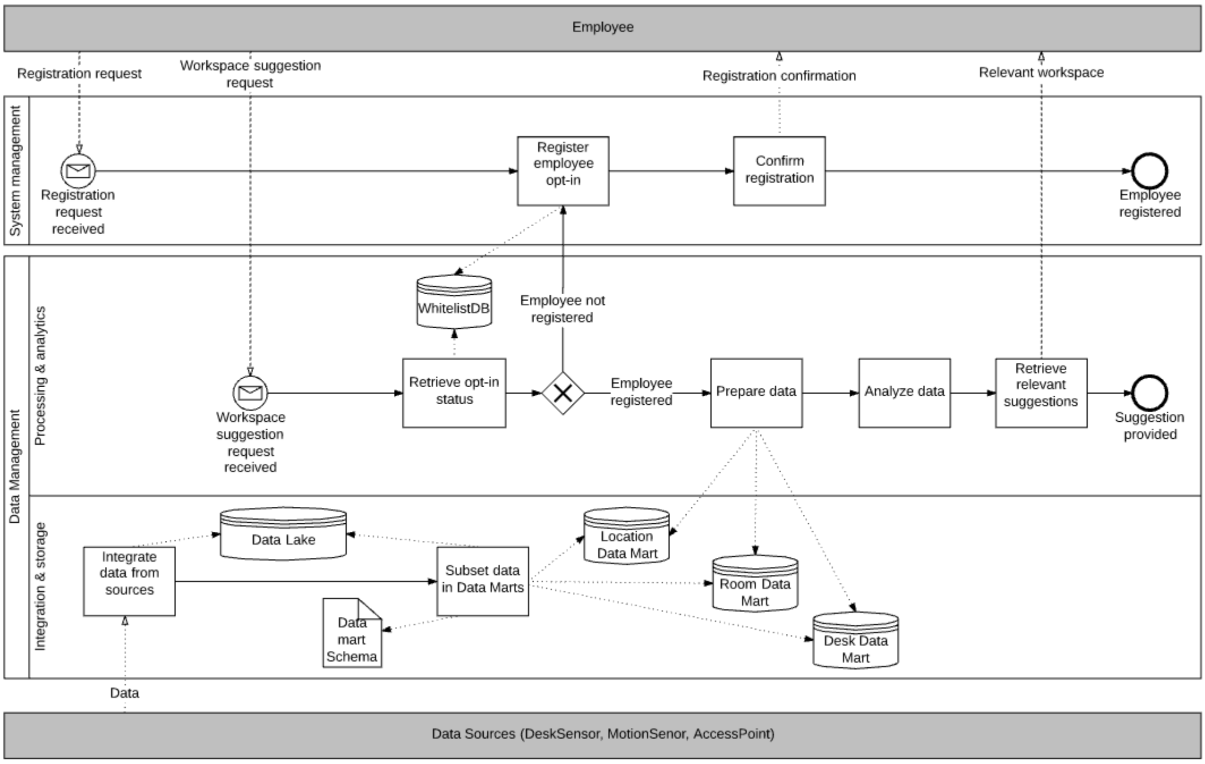



*Figure 18 – Process View System Usage*

In this simple overview two employee interactions are modelled: (1) registering for the system, and (2) the request of suggestions for workspaces. In this model can be seen that employees are able to opt-in for the system and their enrolment is subsequently stored in the *WhitelistDB*. When an employee requests a suggestions for a workspace, this database is consulted to check whether this employee is registered, as a registration is needed before the system can be used. Further, in this model can be seen that the collected data is subsetted in three data marts, one for each data source. These data marts are used to analyse the data and provide the suggestions for workspaces back to the employees.

### *7.5.2. System Implementation*

This process view is used to indicate how the four architectural views that are discussed in this chapter can be used as a reference to derive a *case-specific solution architecture* for the implementation of a workspace optimization solution. This process is modelled using the IDEF0 modelling language (Dorador & Young, 2000) and displayed in Figure 19. The architectural views that are designed in this study are displayed in blue.

For all steps in step in the design of a *case-specific solution architecture* for workspace optimization, *building-specific requirements/constraints* are needed. Also *relevant stakeholders*, such as employees and data scientists need to be involved. For the first step in in this process, the *Context View* needs to be defined in which the scope is set. Input for this activity is the *business goals*, in which the specific use case is defined, and the *WO Context View*, which is designed in this study. The second activity is to design the *Functional View* in which the functionalities of the system are described, followed by the *Physical-Entity View* in which the relevant sensors, physical entities, and virtual entities are defined. Next to that, the *Information View* is defined to visualize the information flow between hardware, software and users. At last, the *Operation & Deployment View* is defined in which the Information View is made concrete with e.g. specific technologies and devices to use. This last view is used for the system implementation. *IoT-A Guidelines* can be used to steer this activity.

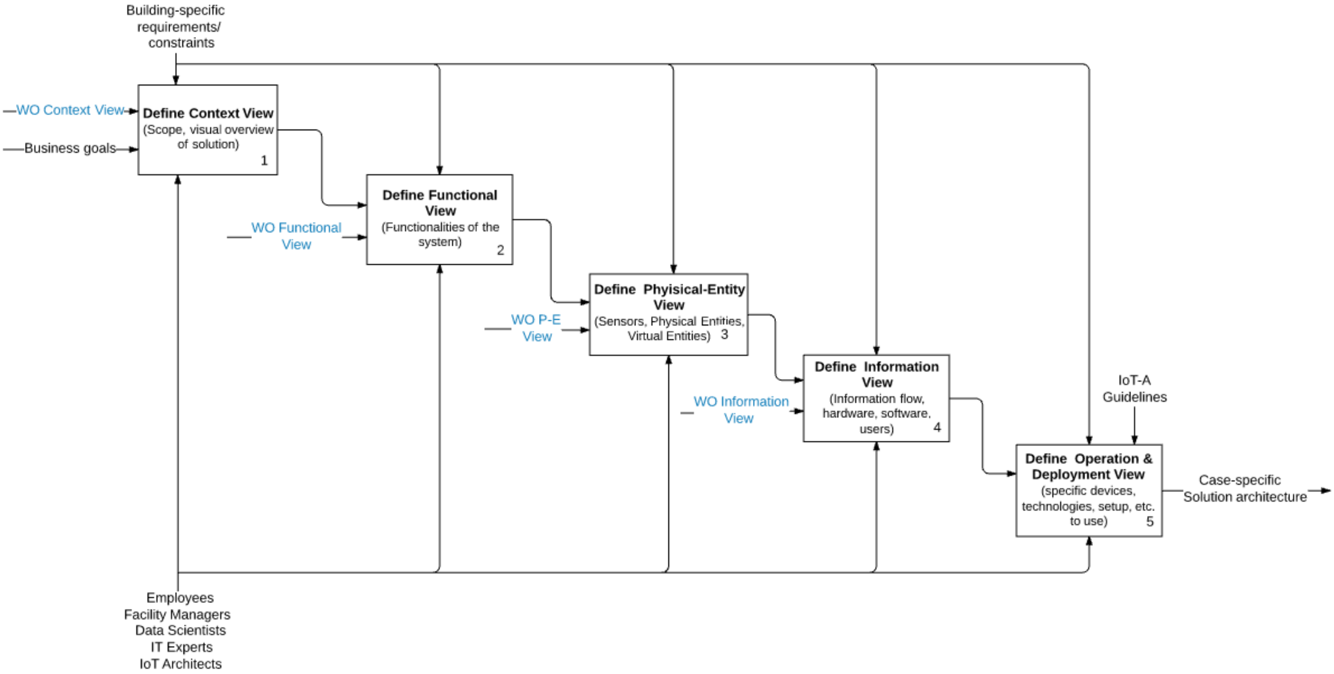



*Figure 19 – Process View System Implementation*

## 7.6. Chapter Conclusion

In this chapter, four architectural views are designed that together form the complete architecture for the workspace optimization solution. First, the Physical-Entity View is described in which an overview is provided of relevant physical entities and devices in the system. In the description of this View is also argued why these devices are needed, based on findings from literature on e.g. occupancy measuring.

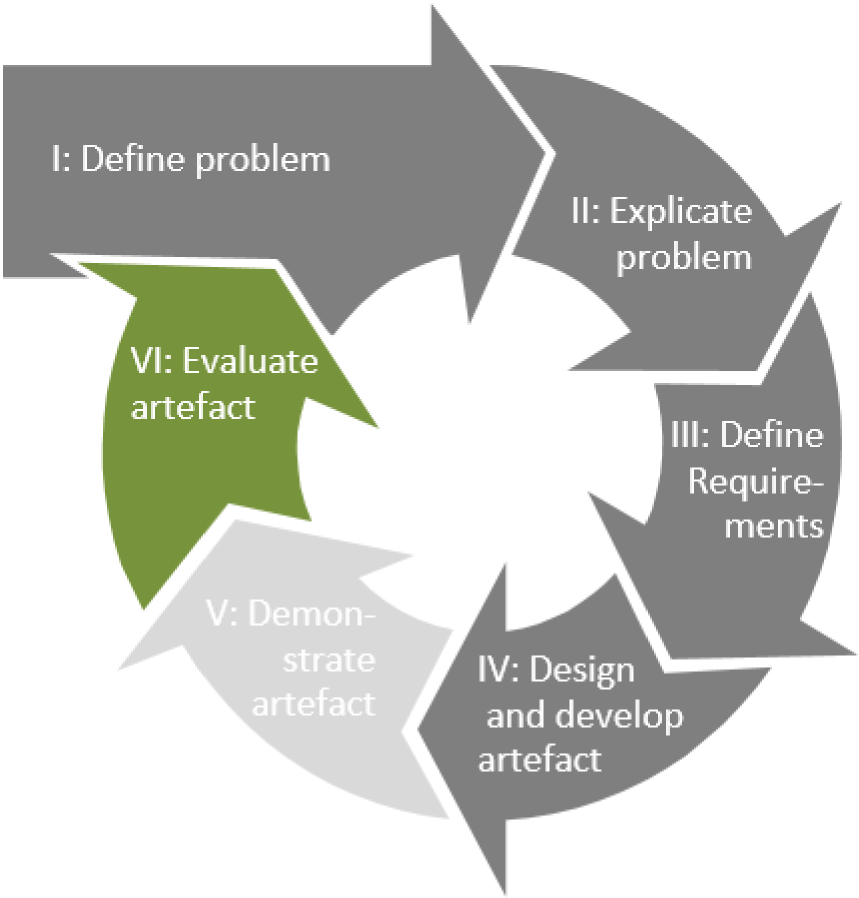
The Context View is provided after that to provide a more tangible overview of the system in place. This is done by displaying the layout of an office floor with several desks, rooms and sensors. This View is mainly used for communication purposes.

Following that, the Information View is described. This View is much more detailed and provides an overview of the information flow in the system. Further, design choices regarding data management are argued here, and supported by findings from the interviews (i.e. requirements for the system).

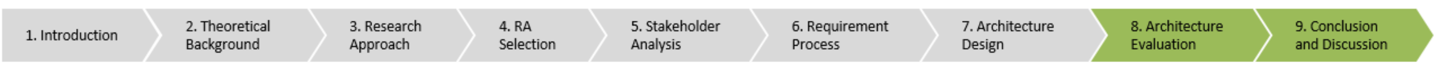
Next to that, the Functional View is provided which offers a high-level overview of functionalities in the system. Design choices regarding Functional Groups (FGs) and Functional Components (FCs) are supported by findings from IoT-A project documents, and by findings from the interviews (i.e. requirements for the system). Further, a specific FG has been added to this View, the *Data Management FG*, in which design choices for data management are explicitly integrated in the Functional View.

At last, two process views have been designed to clarify (1) how the system is used by employees, and (2) how the architectural views are used to define a *solution architecture* that can be used to implement a workspace optimization solution in a building.

# Phase VI: Evaluate artefact




This is the sixth phase of Design Science Framework by Johannesson & Perjons (2014). In this phase the artefact that has been designed in phase IV is evaluated. This is done by assessing how well the artefact is able to solve the explicated problem, as well as to what extent it fulfils the requirements. Further, a conclusion and discussion of the study is provided.




Chapter 8: Architecture evaluation, and Chapter 9: Conclusion and discussion are part of this phase.

# 8. Architecture Evaluation

In this chapter, the four architectural views have been designed are evaluated through interviews with experts. First, criteria for the evaluation are stated, followed by a description of findings from the evaluation process.

According to Johannesson & Perjons (2014), the purpose of artefact evaluation is the following: (1) determining the extent to which the artefact solves the problem as described, (2) evaluate the fulfilment of requirements of the artefact, (3) investigate formalised knowledge about the artefact, and (4) identify opportunities for improvement in further design.

The evaluation process is of an *ex ante*, *formative* nature, meaning that the evaluation is part of an iterative process in which the architecture is still under design – it is not deployed in practice yet (Johannesson & Perjons, 2014). Findings from this chapter will thus be used to improve the architecture. Further, the evaluation is of a *naturalistic* nature, meaning that the architecture is assessed in a real-world setting with real users (Sun & Kantor, 2006). The main strength of these type of evaluations is that multiple stakeholders can be involved, this ensures that various perspectives are taken into account. This is thus very relevant for this study, in which a *multi-actor perspective* is used, as described in chapter 5.

The context of the evaluation is as follows: in chapter 3 is described that semi-structured interviews will be conducted with experts; IoT architects, IT experts, and data scientists to discuss the evaluation criteria, which are stated in chapter 8.1.

## 8.1. Architecture evaluation criteria

The following evaluation criteria are stated for the evaluation process. These criteria are tightly related to the purpose of evaluations, as described in the introduction of this chapter. Also literature on architecture evaluation is consulted to derive additional criteria (Niemi, Hamalainen, & Ylimaki, 2008). See Table 18 for an overview of the evaluation criteria.

| Evaluation criterion | Criterion description | Source |
|---|---|---|
| Effectivity | Effectivity of the proposed architecture to solve the problem as described in phase 2. | Johannesson & Perjons (2014) |
| Feasibility | Feasibility of deploying the proposed architecture in practice | Johannesson & Perjons (2014) |
| Consistency | Consistency of architectural views (also regarding scope) | Niemi, Hamalainen, & Ylimaki (2008) |
| Correctness | Correctness of the used notation in the proposed architecture | Niemi, Hamalainen, & Ylimaki (2008) |
| Interoperability | Interoperability of the proposed architecture with other IoT architectures | Lilis et al. (2017) |
| Sufficiency | Sufficiency of information provided in the proposed architecture and documentation | Niemi, Hamalainen, & Ylimaki (2008) |
| Data management | Integration of capabilities for data management (integration, storage, processing and analytics) in the proposed architecture, as well as handling privacy issues | Burns, (2014), Noronha et al. (2014) |
| Extensionality | Potential for future extension of the proposed architecture | Johannesson & Perjons (2014) |
| Requirement fulfilment | Extent to which the collected requirements are fulfilled | Johannesson & Perjons (2014) |

*Table 18 – Evaluation criteria for the proposed architecture*

For the *Requirement fulfilment* criterion, only the most important requirements are assessed; requirements that are rated as *high priority* in Appendix D. The interview protocol that will be used during the evaluation-session with the four experts (two IoT architects, an IT expert, and a data scientist) is displayed in Appendix E1.

## 8.2. Architecture evaluation findings

The findings of the evaluation interviews are discussed by providing a short description for each criterion. Interesting statements from the experts are provided to substantiate the description in the criterion. A summary of the findings is provided in Table 19. In this table a ✓ represents that the criterion is fulfilled, a ○ means that it is partially fulfilled, whereas a × means that it is unfulfilled.

**Effectivity**

Regarding the effectivity of the proposed architecture, the IoT architects state that it is a very innovative and interesting solution to cope with the dynamics of office occupation: *"this seems a very innovative solution to a problem that I expect to become bigger in coming years"* (IoT architect 2). In addition to that, they state that *"The views look very good, they are clear and especially the context view is useful for providing a concise description of the system"* (IoT architect). They believe that the problem has been described in IoT terms in the right way. Further, this architecture displays what you need for such a solution, but not exactly how the solution works. *"The architecture would be more effective if it had more 'technical' details, e.g. what kind of algorithms should be used"* (IT expert). However, he agrees this would reduce the generalizability of the architecture. *"I understand that you mainly want to describe the system, then this is a very good architecture"* (IT expert). The data scientist argues that the type of data that is collected seems enough to provide suggestions for workspaces: *"On paper it looks right, but of course it will take some time to develop the model and get valuable suggestions"* (data scientist).

**Feasibility**

The experts stated that, even though the architecture looks complete and detailed, it is still quite 'open'. This means that when organizations want to implement this, they have to fill in the details themselves. *"You have a lot of possibilities to fill it in. Because it is so open, it can be implemented easily, and that is a strong characteristic for this architecture"* (IoT architect). This is seen as an advantage for this architecture: *"an architecture should not be too specific, you don't want it to be solved in only way, you should be able to make choices. If it is too specific, you are building a 'solution architecture', and these are not easily generalizable"* (IoT architect).

Further, one IoT architect states that current IoT architectures that are used in practice are very 'technical, but are missing the business context': *"Of course [the technical details] are important, as it is a technical solution, [but] we see that the business context is often missing. It is nice that your architecture also has a focus on this"* (IoT architect 2). The IT Expert and data scientist argue that, even though several sensors are need to be acquired and installed, the architecture seems very feasible with the techniques that exist nowadays: *"it becomes easier to run your analytics in almost real-time, those systems that are needed are not that expensive anymore"* (data scientist).

One note is that the documentation for the architecture is very important to understand the architectural views – just providing the schematics will probably not be enough to understand the system (especially for the Functional View).

**Consistency**

The experts have the opinion that the separate architectural views are indeed consistent with each other. The best example of this is the P-E View, which is one-in-one represented in the Information View. The IT expert and data scientist believe the architectural views are consistent enough, however, the sequence in which the views are presented can be changed a bit to be more logical: *"the scope is the same in the views, however, the Context View is a bit different than the others. This is a good view to start with, the others look consistent in my opinion"* (IT expert). By first presenting the Context View, the following views haven an increasing level of detail, which makes more sense. This is supported by the IoT architect, who states that it makes sense to guide the reader more: *"then you are telling a story that is more compelling"* (IoT architect 2). A comparison is struck with the layers of TOGAF, in which first the business value is modelled. So, after the business goals are explained, the context view should be presented from a user perspective, this clarifies the system scope and business value. After that, an overview of the functionalities and the information that is needed in the system, this is presented in the Functional View: *"This is a combination of technologies and capabilities or functionalities"* (IoT architect 2). The functionalities can then be specified in more detail in a solution architecture, for when you want to implement the system directly. The Information View looks like very much like an information architecture, *"it shows how the information flows and the source-systems that are needed"* (IoT architect 2). At last, the Physical-Entity View can be shown, as it provides even more detail by describing the variables in the database entries.

Further, the IoT architect mentions that the Functional Model indicates two applications to access the IoT system – one for employees and one for facility management. However, the Information View only displays the former. As the views should be consistent, the latter needs to be added to the Information View (IoT Architect).

**Correctness**

The Physical-Entity View and Information View are modelled with UML-Class diagrams. The IoT architects note that this often happens with architectures they develop in practice. *"The UML models look correct to me" (IoT architect).* However, the level of detail is in practice often less than in the proposed architectures – stating whether certain variables are strings/integers is often too detailed for the purpose of their architectures. They argue that this is often only the case when they develop a solution-architecture, but agree that it is good to at least think about the variables that are needed, especially as data management is important in this architecture. The IT expert supports this and claims that especially the information flow in the system is important to think about in the design phase as *"you don't want to be surprised when you implement the system, it is good to know what kind of software and hardware is needed on beforehand"* (IT expert).

Further, the data scientist is slightly confused by the direction of the arrows in the P-E View; *"shouldn't it be that the arrow is towards the sensor instead of the other way around?"* (data scientist). However, UML-class guidelines that are consulted indicate that the direction is correct.

**Interoperability**

Regarding interoperability, the expert agreed that the description of the architectural views in common terms (hardware, software, sensors) helps with the interoperability, as systems can be compared more easily. *"We see these terms always in other architectures, it is good that you describe them in the same way"* (IoT architect). IoT-A was not known by all experts, however, their interest in this reference architecture was raised due to the clarity of the architectural views that are prescribed. The benefit of using common terms to describe the architecture is that differences with other architectures can easily be found – making them interoperable is then easier. For example: *"The way the sensors are described and how they are presented in a database is what we do as well, absolutely"* (IoT architect). This is supported by the data scientist, who states that especially the Information View is important for this, as this View shows e.g. which databases are needed, and how they are being queried. *"This is useful for connecting it to other systems that use the same data"* (data scientist).

Next to that, the Functional View is also widely-used in practice. The IT expert claims that they describe 'clusters' of functions that the systems needs to provide in the design-phase. *"When a concrete solution needs to be developed, these functions are then specified"* (IT expert). An overview of functionalities is thus valuable for identifying commonalities and conflicts among them, this can be used to 'connect' systems.

Further, one IoT architect was familiar with IoT-A *“yes, this is one of the reference architectures that we are also looking at, as well as RAMI, which is more focused on industries”* (IoT architect 2). As they did not find such concrete examples that have applied this reference architecture they were very interested in the outcomes of this study. In their business, they are mostly using architectures that are based on the TOGAF framework, therefore they were curious to see how IoT-A compares to that. IoT-A seems less broad, as it is more focused on IoT aspects, whereas TOGAF is more widely applicable. However, the architect indicates that there are various connection points that show potential for interoperability between TOGAF and IoT-A architectures (IoT architect 2).

**Sufficiency**

In general, the experts were quite positive with the level of detail that is provided in the architectural views. One IoT architect states that even though the views are quite detailed, they are not too complex, they are easy to understand. For the Functional View, the expert stated: *“I think this is a very good picture. I don’t know IoT-A, but they describe all the concepts that you would expect. The additions that are made are clear as well”* (IoT architect). Though, there were also recommendations to improve the architectural views: *“the views look good, but I would add a legend to all of them, the context view can become much clearer, and the colours in the Functional View are not explained at all”* (IoT architect).

The IT expert and IoT architect state that the Information View is now a bit confusing, it can be simplified a bit more by reducing the level of detail: *“If you want to show the relationships between components in the Information View, it is not necessary to show what the variables are exactly, this is already provided in the [Physical-Entity View]”* (IT expert). This is supported by the data scientist who shortly describes their architectural process: *“We mostly make it specific for a solution. We start with a functional design in which the goal of the solution is described, e.g. combining data of three sources in a data lake. We specify how the data needs to be processed etc. Thus, in the functional design the system is described for the end-user in easy language. On top of that a technical design is made by a BI architect who specifies the techniques that need to be used, e.g. what is the best way to retrieve data from an API or from a cloud database. This is all described step-by-step. This also has specific details regarding the size of the servers that are needed, how long the process takes, etc. This technical design is being used by our developers to write the code/script/ETL process. The technical design looks a bit like your Information View”* (Data scientist). Thus, the level of detail in the architectural views are argued to be sufficient for the first steps in the process.

**Data management**

For the integration of data management in the IoT architecture, a new FG has been added to the Functional View. This FG houses all FCs that are related to data management of the IoT system, as described in chapter 7. According to experts, it is quite strange that IoT-A did not include FCs regarding data management, they think this is due to high-level nature of the architecture, and that the researchers deemed analytics are just part of e.g. the IoT service FG. However, *“IoT is so data-driven, I am convinced that it deserves a place in this architecture, so I am sure it is a good addition” (IoT architect)*. The importance of data management is also what they see in practice *“If you collect data from all kinds of sensors, you need to have a structured way of working to handle that. You need to have clear agreements regarding the data model and quality of source data”* (IoT architect 2). However, both the IT expert and data scientist argue that it might be better to make the Data Management FG part of the IoT Services FG, as they are tightly linked – data management is needed for the functioning of IoT Services. This also allows the interrelationships between FGs to remain as they are prescribed by IoT-A, while a specific focus on data management is added.

Regarding design choices for data management, the IT expert argues that centralized data processing & analytics is indeed a good option for this solution, as the data is collected and stays within the office. Network constraints are thus less of an issue, compared to e.g. an IoT solution on a ship in which data needs to be sent over satellite. *“I don’t think e.g. desk sensors change their state that often, edge* *computing is thus not really needed I guess"* (IT expert). Data can be send to a centralized location when there is an event: *"you can send data to a database when there is a change, in an office there is no issue with the network"* (IT expert).

The data scientist agrees that a centralized solution for data integration & storage is beneficial, however, he states that it might be a better idea to use a data lake instead of a data warehouse. *"If you use a data warehouse, you have to specify the type of data exactly on beforehand. It is easier to use a data lake, then you can store all the data"* (data scientist). It is argued that having all the data can be useful for future use – additional use cases can be developed and trends can be discovered more easily as more historical data is stored. In this case, one big data lake is used to store (almost) all data, and several data marts are designed that consist of structured and cleaned data for querying. *"Otherwise you leave out a big piece of raw data – you lose it"* (data scientist). Regarding privacy, a current best practice is to leave out privacy sensitive data *"If we have personal data, e.g. salary scales, then we just leave it out, or hash the values"* (data scientist). Another idea to protect the privacy of employees is to aggregate the data on e.g. team-level: *"as long as you aggregate the data, you are allowed to store it, because there is no name attached to it. This can still be used to provide suggestions to an employee, as the location of their team members is known and stored"* (data scientist).

Further, the expert notes that it is important to consider whether the source (device) is able to provide real-time data: *"We often work with APIs, we send some instructions to the API and we receive the data back. If this is around 100GB per 15 minutes, it takes a huge strain on the network, and the SQL database needs time to process the data"* (data scientist). If that is the case, a cloud solution is argued to be beneficial, as this increases the amount computational power that is available.

**Extensionality**

The respondents argue that potential for future extension is mainly due to the fact that a modular architecture has been created before the systems is developed. *"In general, systems are more manageable and future-proof if you think them through [by creating an architecture on beforehand]"* (IoT architect). For the proposed architecture, the addition of data management components are therefore a good addition, as *"IoT is so data-intensive that you really need to think about the way you will handle the data streams"* (IoT architect). In particular the modularity of components in the architecture improves with the manageability and future proofing of the system: *"which often still lacks in the world of IoT"* (IoT architect 2).

Further, it is stated that the fact that the proposed architecture isn't too detailed supports for future extension of e.g. new use cases. *"You can replace the desks with something else, or change the sensors, and the rest is then still the same, so it can be applied again, that is good"* (IoT architect 2). Both the IT expert and data scientist agree that the high-level nature of this architecture allows for new use cases can be added relatively easily. It is possible to slightly alter this architecture without completely overhauling it: *"when you have a new use case based on the same data, it is possible that you change the type of analytics within that component, but the architecture itself does not change, that is really good"* (IT expert).

**Fulfilment of requirements**

For this criterion, the requirements that are rated as *high priority* are presented to the two IoT architects that are interviewed for the evaluation. The architects are asked to take a closer look at the architectural views, to read the documentation carefully, and to state to whether they believe the requirement is fulfilled by the proposed architectural views. The findings for this criterion are presented in Appendix E2. In short; only a few requirements were rated as unfulfilled. This was for example due to difficulties to rate them (e.g. the requirement whether the system is easy-to-use and understand) without a working solution: *"a separate study on user perception might be needed to be able to rate that"* (IoT Architect). In other occasions certain functionalities of the system needed to be explained more thoroughly.

## 8.3. Chapter Conclusion

In this chapter the architecture evaluation process is described by first presenting evaluation criteria, and consequently findings from interviews that are related to these criteria. A summary of the findings is provided in Table 19.

| Expert | Effectivity | Feasibility | Consistency | Correctness | Interoperability | Sufficiency | Data management | Extensionality |
|---|---|---|---|---|---|---|---|---|
| IoT Architect | ✓ | ✓ | × | ✓ | ✓ | ○ | ✓ | ✓ |
| IoT Architect 2 | ✓ | ✓ | ○ | ✓ | ✓ | ○ | ✓ | ✓ |
| IT Expert | ○ | ✓ | ✓ | ✓ | ✓ | ○ | ○ | ✓ |
| Data Scientist | ✓ | ✓ | ✓ | ○ | ✓ | ✓ | ○ | ✓ |

*Table 19 – Summary of expert evaluation, a ✓ means fulfilled, a ○ partially fulfilled, and a × means unfulfilled*

Interestingly, from this overview becomes clear suggestions for improvement are mainly provided for the *Consistency, Sufficiency,* and *Data management* in the proposed architectural views. Next to that, it becomes clear that the experts have varying opinions about the evaluation criteria, e.g. on *Consistency*, the first IoT architect states this criterion is unfulfilled, the second IoT architect states it is partially fulfilled, whereas the IT expert and data scientist reason that this criterion is fulfilled.

Therefore, their opinions will be handled as follows: first, efforts will be made to include all suggestions that the experts provide. Next to that, some criteria are more linked to a certain expert, e.g. the data scientist knows more about *Data Management*, thus their opinion on this criterion is perceived as more important.

Handling the expert evaluation in this way results in the following suggestions for the architectural views:

- Improve consistency by adding legends to all views, and by changing the order of the architectural views.
  - The views are inconsistent, some views have legends, others have not
  - Start with the Context View, which sets the scope clearly and is least abstract, then Functional view to describe the full system, Information View to show the interrelationships and information flow, and P-E View for more details on database attributes
- Less detail is sufficient for the purpose of these views
  - The purpose of the Information View is to show how hardware, software, and users are related. Specific details, e.g. database attributes, are already provided in the P-E View, thus they can be removed from the Information View.
- Move the Data Management FG inside the IoT Service FG, and rethink design choices regarding data integration & storage
  - Components that are related to data management are tightly linked to IoT Services. Therefore, it might be better to show these components as part of the IoT Services FG. This also allows the current interrelationships between the FG's to remain as IoT-A provides it.
  - Use a data lake with several data marts instead of a data warehouse – this might be more useful for future use cases, as all raw data is stored

A redesign of the architectural views that includes these suggestions is provided in Appendix F. Design choices regarding capabilities for data management and privacy constraints are explicated in the Information View (Appendix F3).

# 9. Conclusion and Discussion

In this chapter the study will be concluded by answering the research questions that have been stated, and by describing the scientific and practical contributions of this study. Further, there is a discussion section in which is reflected on the research process by discussing limitations of the study and directions for future research.

In this study, an IoT architecture is developed for *workspace optimization in smart buildings*. In foregoing chapters, the complete architecting process – and related research process – has been thoroughly described. At the end of each chapter a short chapter conclusion has been provided that concludes the findings in chapter. In *this* chapter, a conclusion is provided for the *whole* study, and the main research question is answered.

## 9.1. Conclusion

Several knowledge gaps are identified in this study. Firstly, the problem of increasingly dynamic office occupation is stated as a starting point for this study. A potential solution for this, *workspace optimization* based on IoT devices (i.e. sensors) in buildings is found to lack research; a structured design/architecture that can be used to design and implement such a solution is missing.

Secondly, a more fundamental problem is IoT solutions is that they are not based on common guidelines. Due to different approaches to the design of these solutions, they cannot communicate effectively with each other, whereas interoperability between IoT solutions is vital for the rise and success of smart cities.

Thirdly, a need for common understanding between stakeholders that are involved in IoT use cases is found, as deployment of IoT systems in e.g. cities (i.e. smart cities/smart buildings) require cooperation of multiple parties.

At last, a lack of focus on capabilities for data management is identified in IoT solutions, as the focus is more on connecting as many devices, whereas researchers argue that combining this with sufficient data management capabilities (e.g. integration and analytics) can lead to more value, both now and in the future. This is in particular relevant as privacy-sensitive data is collected, by taking measures in the design-phase already, both compliancy with privacy regulations and value from the solution can be attained.

Based on these research gaps, the main research objective for this study was presented as follows: the research objective is to develop an IoT Architecture for workspace optimization in smart buildings that complies with the following requirements:

- The architecture is based on common guidelines and architecture standards that are supported by agencies to improve interoperability with other IoT solutions
- The architecture is scalable, external data sources can be added over time
- The architecture reflects the concerns of the various stakeholders that are involved in order to include them in the discussions
- The architecture integrates capabilities for data management in the design

The following main research question has therefore been stated:

What are the design specifications of an interoperable IoT architecture for workspace optimization that integrates capabilities for data management?

The following sub questions are stated to answer the main research question, and to structure the research process:

1. What are the defining characteristics of interoperable IoT architectures?
2. What are the requirements for an IoT architecture for workspace optimization in smart buildings and which relevant parties need to be involved?
3. How can a focus on capabilities for data management be integrated in IoT architecture design?
4. What are evaluation criteria and how do experts evaluate the proposed IoT architecture for workspace optimization in smart buildings?

For additional guidance and structure in the architecting and design process, the design science framework by Johannesson & Perjons (2014) has been applied in this study. The architecting steps have been described thoroughly in foregoing chapters.

With the knowledge that is obtained from this study, the sub questions can be answered as follows:

**1. What are the defining characteristics of interoperable IoT architectures?**

This question can primarily be answered through findings in chapter 2: Theoretical Background. Here is described that IoT architectures are being used to provide understanding of the important parts in a system, how they work together, and how they interact with their environment. Architectures are particularly useful for the design and development of systems. Architectures are often depicted through a combination of views. These architectural views describe the system from a specific perspective, e.g. a functional view describes the functionalities of the system, whereas the context view describes the context and system scope. IoT architectures are in particular needed, because IoT solutions ask for (relatively novel) knowledge about the combination of software, IT needs and technologies

Reference architectures are general architectures that are helpful in the design and development of concrete architectures, because they are characterized by sets of best practices and essentials for the development of systems. Reference architectures have a particular focus on interoperability between solutions, as common guidelines are provided. In IoT context, these reference architectures prescribe e.g. how IoT devices need to be connected and organized, as well as their relationship with physical entities that these devices monitor, the software, and their environment.

**2. What are the requirements for an IoT architecture for workspace optimization in smart buildings and which relevant parties need to be involved?**

This questions can primarily be answered through findings in chapter 5: Stakeholder Analysis and chapter 6: Requirement Process. Here is described that the proposed IoT architecture for workspace optimization needs to comply with 46 requirements that have been collected through a desk study and interviews. An extensive list of these requirements and their characteristics (such as type and fit criterion) is provided in Appendix D. These requirements have been collected by involving the following stakeholders in the process: employees, facility managers, data scientists, information systems managers, and privacy officers. These stakeholders' were selected to include in the process based on their power and interest in the system. Other stakeholders, such as the building owner, are less relevant for this system, thus they are not included in the requirement process.

Based on the findings from the requirement process, it becomes possible to provide a priority-rating to the requirements. In total, 26 requirements are rated with a *high* priority and are thus important to take into account for the system design. The high priority requirements are displayed in Table 20.

| UNI ID | Description | Requirement Type |
|---|---|---|
| UNI.001 | Users are able to use the service anonymously | Non-functional |
| UNI.002 | Users have control how their data is exposed to other users | Non-functional |
| UNI.005 | The system supports event-based, periodic and/or autonomous communication | Functional |
| UNI.016 | The system supports physical entity location tracking (logical location) | Functional |
| UNI.018 | The system supports capabilities for data management (integration & storage, processing & analytics) | Functional |
| UNI.050 | The system supports mobile physical entities | Non-functional |
| UNI.062 | The system provides trusted and secure communication and information management | Design constraints |
| UNI.067 | The system provides different access permissions to information | Functional |
| UNI.410 | The system restricts who can update and delete Digital Entity history | Functional |
| UNI.414 | The system enables the dynamic discovery of virtual entities and their services | Functional |
| UNI.423 | When performing discovery, resolution or lookup, the system must respect any aspect of privacy, including the possibility to retrieve information about or related to people. In addition some services should be accessible in an anonymous way, while others might require an explicit authentication or authorization of the user. | Functional |
| UNI.502 | The system prevents a device from being activated without the consent of the owner. | Non-functional |
| UNI.503 | The system makes it be possible to change the owner of a device | Functional |
| UNI.504 | The system prevents tracking of the identifier of the device by unauthorized entities. | Non-functional |
| UNI.506 | The system supports communication across devices by aid of standardized communication interfaces. | Design Constraint |
| UNI.606 | The system makes the traceability of digital activities impossible | Non-functional |

| Req.ID | Description | Requirement type |
|---|---|---|
| 1. | The system enables employees to disable tracking (opt-out) | Functional |
| 2. | The system needs employees' approval to start tracking them (opt-in) | Functional |
| 4. | The system is able to find IoT devices automatically | Non-functional |
| 5. | The system determines the employee's location based on the location of their laptop | Functional |
| 8. | The system collects and stores user identifiable data | Non-functional |
| 9. | The system needs to have a high accuracy of suggestions | Non-functional |
| 10. | The system needs to be able to work in real-time | Non-functional |
| 11. | The systems needs to be easy to use and easy to understand | Non-functional |
| 12. | The system allows employees to provide their preference for a workspace | Functional |
| 16. | The system supports various user permissions for the system | Functional |

*Table 20 – High priority requirements for a workspace optimization solution*

### 3. How can a focus on capabilities for data management be integrated in IoT architecture design?

This question can primarily be answered through findings in chapter 2: Theoretical Background and chapter 7: Architecture Design. In chapter 2 several capabilities for data management have been defined: data integration & storage, and data processing & analytics. Also several design choices that can be made for these capabilities are discussed (such as centralized integration & storage in a data lake). In the Functional View of IoT-A, the reference architecture that has been selected to provide common guidelines, a functional group (FG) is added to indicate the importance of data management in IoT architectures (see Figure 21). The addition of this FG forces system designers to make design choices regarding data management in the system design.

In addition, a simple visualization is presented (Figure 20) that displays (non-exhaustive) design choices that an IoT architect can select, e.g. a *data warehouse* as a *centralized* solution for data integration & storage, combined with *real-time, decentralized* processing & analytics. Adding this data management FG to the IoT-A reference architecture, forces system designers to focus on these capabilities in the design phase already. Further, presenting them with options to select makes it easier for systems designers to choose the capabilities that are best fitting for their envisioned IoT system.

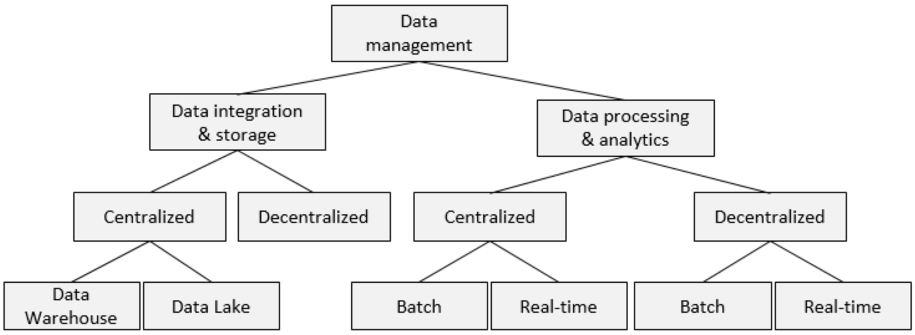


*Figure 20 – Design choices for data capabilities in IoT systems*

**4. What are evaluation criteria and how do experts evaluate the proposed IoT architecture for workspace optimization in smart buildings?**

This question can primarily be answered through findings in chapter 7: Architecture Design and chapter 8: Architecture Evaluation. Evaluation criteria for the proposed architecture in chapter 7 are stated by consulting general literature on artefact design, as well as more specific research or architecture evaluation. The following requirements are used in this study: *Effectivity, Feasibility, Consistency, Correctness, Interoperability, Sufficiency, Data management, Extensionality,* and *Requirement fulfilment*. In chapter 8 is described how four experts (2 IoT architects, 1 data scientist, and 1 IT expert) evaluate the proposed architecture for workspace optimization in smart buildings.

In general, the experts have a positive view on the architecture, in particular the effectivity of the architecture to describe important parts of the system in several architectural views is seen as positive, as well as the use of IoT-A for common grounding and the addition of a specific FG for data management. One experts was more critical on the feasibility to use these views to design a concrete solution, whereas another expert stated that the generic level of the architecture was a positive point. As the proposed architecture has not demonstrated in this study (e.g. by specifying exactly the sensors and algorithms that need to be used), this point of criticism was expected. Further, some criticism has been given on consistency of the various views; the sequence of the views, the placement of the data management FG, as well adding legends were provided as suggestions for improvement of the architecture. Based on the suggestions provided by the experts, the architectural views have been redesigned.

**Main research question**

The answers of these sub questions can together be used to answer the main research question as follows:

The expert-evaluated architecture for workspace optimization in smart buildings has been designed using common guidelines from the IoT-A reference architecture to improve interoperability, and includes explicit notions of capabilities for data management to integrate this in the system design.

The following architectural views are specified and designed to provide a complete overview of the envisioned IoT system:

- Context View: sets the system scope and provide a clear visualization of important parts of the system (Appendix F1)
- Functional View: provides a detailed description of functions in the system, grouped in functional components and functional groups (Appendix F2)
- Information View: provides an overview of relations between important users, hardware and software in the system, as well as the information flow (Appendix F3)
- Physical-Entity View: provides a detailed description physical entities, their digitally represented virtual entities, and important IoT devices (Appendix F4)

Next to that, two process views are designed that provide a better understanding of (1) how the system is used by users, and (2) how the four architectural views can be used to derive a specific *solution architecture* for the implementation of such a system.

Together, the architectural views and process views provide a complete description and overview of a solution for workspace optimization in smart buildings.

## 9.2. Discussion

In this section is reflected on this study by discussing the scientific and practical relevance, the limitations, and directions for future research.

### *9.2.1. Scientific relevance*

The scientific contribution of this study is as follows: first of all, the research field of *workspace optimization* is relatively nascent, as existing studies are mostly focused on small-scale test settings for occupancy measuring techniques in buildings. An architecture for the design and implementation of a workspace optimization solution is found to be lacking, e.g. on how the data should be managed and how the privacy constraints needs to be handled. Further, in section 2.1 is stated that four high-level, conceptual requirements for such a solution are described in literature: *low cost*, *non-intrusiveness*, *high accuracy*, and *privacy-preserving*. In this study, a stakeholder analysis is performed to identify relevant stakeholders for such a solution. Through interviews with these relevant parties, 46 more specific requirements have been identified and prioritized, resulting in 26 *high priority* requirements (see Table 20). These requirements are subsequently used to design 4 architectural views, and two additional process views to support the design and implementation of such a solution.

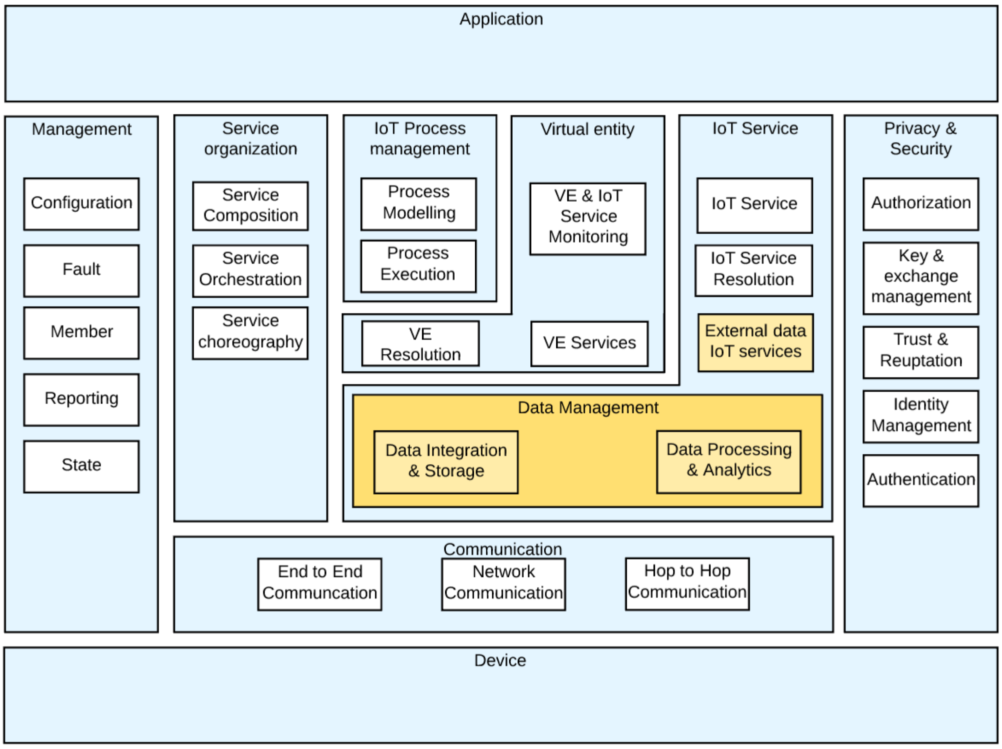



*Figure 21 – Proposed extension to IoT-A Functional View*

Further, research suggests that IoT systems can be more robust and more value can be gained from them if there is a clear and specific focus on capabilities for data management in the design phase of these systems. However, at this moment, organizations focus more on connecting devices, and data management is dealt with in a later phase. The reference architecture that is used in this study to structure the design and to provide guidelines and concepts, IoT-A, is found to lack an integration of data management. Therefore an extension of IoT-A's Functional Model in is proposed in which data management is integrated. This extension adds the *Data Management FG* as a subgroup inside the *IoT Service FG*, as capabilities for data management are tightly linked to IoT Services. Also a FC for *External data IoT Services* is added, as can be seen in the proposed extension in Figure 21. By integrating the *Data Management FG* as a subgroup, existing relationships between the FGs remain as they were proposed by IoT-A. Further, a simple overview of design choices in IoT systems is provided that can be used by system designers to select the suitable design choices to integrate in their system (Figure 20).

#### *9.2.2.Practical relevance*

Next to that, this study has also practical contributions. First of all, specific IoT use cases in smart buildings are needed to stimulate the development of smart cities. Researchers state that a lack of specific use cases hampers the development of smart cities, as the added value of sensors and extensive data collection in e.g. buildings needs to be proven first. The business value needs to be explicated to convince the various stakeholders that are involved in smart city-projects of the added-value of IoT in buildings and cities; concrete examples are needed for this. This study discusses and proposes a concrete IoT use case, and consequently, stimulates IoT development.

Further, facility managers or real estate developers that are interested in a solution to cope with dynamic occupation in their (smart) buildings, are presented with an IoT architecture for workspace optimization that is based on a widely used reference architectures. This architecture can be used to specify a building-specific architecture and subsequently implement (see section 7.5 for this process) a workspace optimization solution in offices to e.g. optimize the energy usage, or to make it easier for occupants to find vacant desks/rooms. Also, the common grounding on which this architecture is based improves interoperability with other use cases/applications that are based this reference architecture.

At last, for Deloitte, who cooperates with this study, these findings are especially relevant. Their Amsterdam office can be seen as a smart building, *without* a solution for workplace optimization. However, this is desired, as it is challenging to find vacant desks or rooms on busy days. This architecture can be used to facilitate communication among the stakeholders that are involved in such a process, as well as serve as a guideline for the design of such a system.

#### *9.2.3.Limitations*

Even though this study has been executed carefully and with much effort, there are always limitations. First of all, and most importantly, the demonstration of the proposed architecture is out-of-scope for this study due to time constraints. Ideally, this phase would also be performed, as it would provide a 'full design cycle'. Also, the evaluation-phase would perhaps be more valuable if a concrete architecture could be presented to the experts.

Next to that, in chapter two, four capabilities for data management are identified and discussed. However, it is stated that there is no agreement on data management capabilities among researchers, as a variety of capabilities were found that were e.g. named (slightly) different. Also, several of the *data lifecycle management* descriptions that were studied are varying; some state 7 steps, others 6, and others 4. Due to this lack of consistency, four capabilities were selected and defined that were present in most lifecycles (although sometimes named slightly different); *integration*, *storage*, *processing*, and *analytics*. Thus, it is important to be aware that other capabilities exist as well (e.g. sharing of data).

Further, several design choices are provided in this study that can be made by system designers regarding data management, e.g. a *data warehouse* as centralized solution for data integration & storage. However, numerous other choices are possible (e.g. hybrid solutions), thus a more sophisticated framework is needed that can be used by system designers to decide on the most suitable capabilities for their system.

At last, there are two limitations related to the interviews that are conducted. In round 1, several stakeholders were interviewed to gather requirements for the for the architecture design. A stakeholder analysis is performed to identify the relevant stakeholders; in total nine stakeholder-groups were found. However, only the most important ones; 5 stakeholder groups, were interviewed. Even though 16 interviews were conducted for the requirement elicitation process, it was not possible to interview everyone (from all nine groups) due to time constraints. For example building owners are not interviewed whereas they might be able to add interesting perspectives. Also, only one privacy officer is interviewed, as there was only one privacy officer in the case setting. In round 2, interviews are conducted with experts to evaluate the architecture. However, due to the time limitation of this study, as well as availability of respondents, only four interviews are conducted for the evaluation; two IoT architects, an IT expert, and a data scientist are interviewed. As a result of this, the opinion of these experts have a relatively high weight, compared to the respondents in round 1. Related to that, in section 8.3 is described that the opinions of these experts were not always consistent, sometimes they were even conflicting. This has been handled by linking some criteria to one expert, e.g. the opinion of a data scientist is more valuable for the criterion *data management* than the IT experts' opinion. Ideally, these conflicts would be solved by organizing a focus group session with all experts to discuss these conflicts. Unfortunately this was not possible for this study due to agenda issues.

#### *9.2.4.Directions for future research*

At last, some directions for future research are provided. First of all, the proposed architecture has not been demonstrated (e.g. by deriving an *Operation and Deployment View*), as this was out-of-scope for this study. However, a demonstration is valuable as it explicates how the architecture can be used in practice, thus future researchers are able to use the architecture views that are developed in this study to deploy it in practice. This architecture can also be improved by future researchers as newer techniques emerge (e.g. derive desk occupancy based on WiFi sensors). The main advantage of this architecture is that due to the modularity such changes can be applied easily (e.g. by changing the type of IoT device, as desk sensors are then no longer needed).

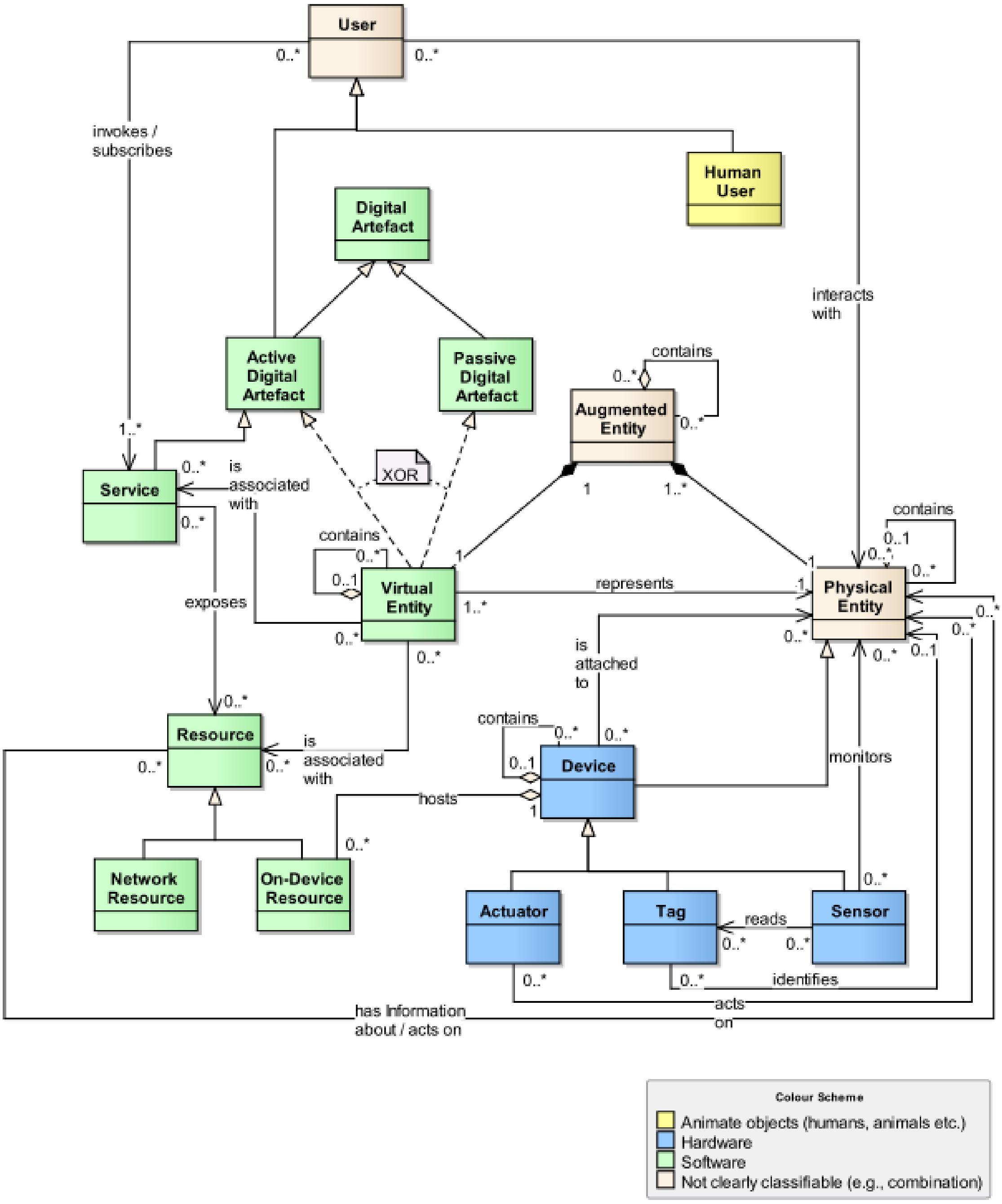
Another direction for future research is to design a sophisticated framework that can be used by system designers to select to most suitable design choices to integrate in their system design. As stated in the limitations, only four capabilities are discussed in this study, and a relatively simple overview of choices is provided. By developing a sophisticated decision framework, IoT architecture design can be streamlined even more.

At last, an extension to IoT-A's Functional View is provided in this study. Researchers that work on IoT-A can validate the findings in this study and improve their architecture by integrating this new *Data Management FG* in their regular reference architecture to ensure that IoT systems designers consider this from the start of their system design. Further, researchers that are working on other IoT reference architectures can take this study as an example and integrated *data management* in their reference architecture as well.

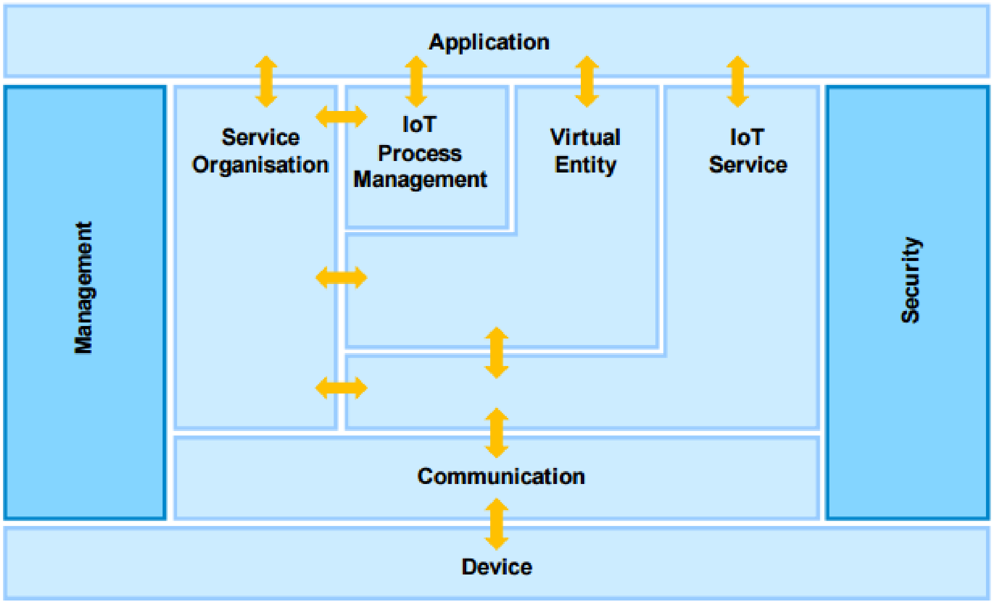
# Appendices

## Appendix A: IoT-A Models and Views

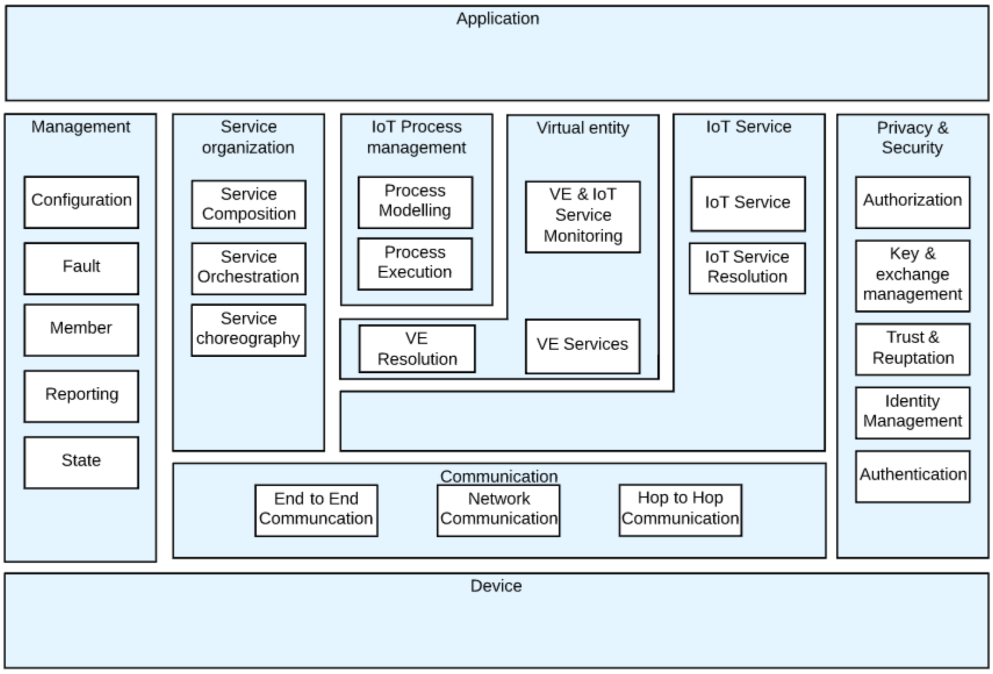
### *A1: UML representation IoT Domain Model (IoT-A)*



*A2: IoT-A Functional Model*




*A3: IoT-A Functional View*



## Appendix B: Volere requirements shell

The following Volere requirements shell is used in this project. The shell is based on the IoT-A project deliverables (Bassi et al., 2013; Carrez et al., 2013), deliverables from projects that have applied IoT-A (COSMOS, 2017; FIESTA, 2017), and Volere documentation (Robertson & Robertson, 2012).

| Attribute | Description |
|---|---|
| Unique ID | ID to identify the requirement |
| Requirement Type | Specifies the type of requirement. Volere templates consider the following main type of requirements (Bassi et al., 2013; Robertson & Robertson, 2012):<br>• Functional requirements: describe what the architecture has to do<br>• Non-functional requirements: properties that the functions must have, e.g. performance or usability<br>• Design constraints: restrictions on design, e.g. use existing setup of devices |
| Priority | The priority of a requirement, based on the priorities given to the requirement by the various stakeholders, and the importance of the stakeholders. Priorities are rated as: High/Medium/Low |
| Description | A statement of what the requirement has to fulfil |
| Fit criterion | A measurement of the requirement such that it is possible to test if the solution matches the original requirement |
| Conflicts | Conflicts between requirements. There exists contradiction between stakeholders, or one requirement makes the other less feasible |
| Stakeholder | Stakeholder(s) that raised the requirement, if applicable |

## Appendix C: Architecture design

***C1: Interview guide round 1***

**Introduction**

This interview concerns *workspace optimization in smart buildings* through IoT sensors. The use cases are:

- Finding vacant desks and meeting rooms in the building
- Finding the location of colleagues in the building

Through a smartphone application, the user is able to see vacant desks and meeting rooms, find the location of their colleagues, and see suggestions for desks (workspace optimization).

This data is collected through: WiFi Access points, desk sensors, and motion detectors in rooms.

**Open Questions**

1. What are important considerations for a workspace optimization solution from your perspective?
2. What are obstacles for this solution can you foresee?
3. What would you consider the (technical) issues that need to overcome for such a solution to work?
4. What are potential negative consequences of such a workspace optimization solution?

**Additional questions for specific stakeholders**

Employee

1. As a potential user of the system, would you use the workspace optimization solution as described?
2. Do you think this improves your working experience?
3. Are you willing to take some actions yourself for such a system to work (e.g. check in)?

Facility manager

1. Do you think that such a solution increases the value of the building?
2. Do you think this solution improves the working experience of employees?

Data scientist

1. Do you think this solution improves the working experience of employees?
2. What are important considerations for this solution, from a data perspective?
3. What needs to be taken into account in the system design to facilitate data analytics?

Information systems manager

1. Do you think this solution improves the working experience of employees?
2. What are important considerations for this solution, from an information system perspective?
3. What needs to be taken into account in the system design regarding information systems (e.g. scalability, performance, data management constraints)

Privacy officer

1. Do you think that users would like to use a workspace optimization solution as described?
2. What are important considerations for this solution, from a privacy perspective?
3. Do you think that such a solution is feasible without harming users' privacy?

**Closed Questions**

Please rate the statements in question 1-10 on their importance, then select the three most important qualities of a workspace optimization solution in smart buildings.

| Question | Not important | Slightly important | Moderately important | Important | Very important |
|---|---|---|---|---|---|
| 1. What do you think about a solution for finding vacant desks in the building? | | | | | |
| 2. What do you think about a solution for finding the location of colleagues in the building? | | | | | |
| 3. How important do you consider it that the service can be used anonymously? | | | | | |
| 4. How important do you consider it that you have control over who your data is accessible to? | | | | | |
| 5. How important is it that this service is available in real-time? | | | | | |
| 6. How important is it that historical information is stored? | | | | | |
| 7. How important is it that the system provides different user access permissions to the information? | | | | | |
| 8. How important is it that the system takes external computing resources (e.g. the cloud) into account? | | | | | |
| 9. How important is it that data requests are stored? | | | | | |
| 10. How important is it that users explicitly need to authorize that they can be found? | | | | | |

| 11. What do you consider the most important qualities of a workspace optimization solution in the building? (Rank them from 1 – most important, to 4 – least important) | | |
|---|---|---|
| Security & privacy | A secure platform and compliant handing of sensitive data | [ ] |
| Availability & resilience | Uptime of the system and handling of failures | [ ] |
| Evolution & interoperability | Cope with changing technologies and evolving software | [ ] |
| Performance & scalability | Cope with significant growth in usage and perform fast | [ ] |

**(See Appendix D1 for a mapping of the closed questions and the corresponding UNIs)**

***C2: Interview findings round 1***

The findings from the interviews are described here as follows: the first column displays quotes/statements that can be seen as requirements, which are stated in the second column.

**Open questions**

| Quote/statement | Corresponding requirement |
|---|---|
| "It is important that I can (temporarily) turn of that my location can be found" (#1)<br>"Perhaps you need to incorporate in the design that people don't want to be tracked sometimes" (#2)<br>"Privacy is very important, by law people should be able to opt-out" (#7)<br>"You have to convince people to start using this, you have to offer them more" (#7)<br>"If you don't let people opt-out, they will protest" (#7)<br>"Personally it is no issue that I can be found, but I can image that this is an issue for others. Perhaps let them (temporarily) turn it off" (#8)<br>"If people don't want to use this, you cannot force them to, otherwise you can lose your employees or even get bad press" (#14) | The system enables employees to disable tracking (opt-out) |
| "Privacy is a huge concern here, so I think this will only work is you give the choice to the users" (#2)<br>"I think that the advantages are not bigger than the privacy infringement. It might help if I opt-in for the moment that I want to share data" (#10)<br>"We have the assumption that people are willing to opt-in as long as it is attractive enough" (#11)<br>"People can be persuaded by stating that they only find vacant desk as they share their location" (#11)<br>"Privacy law simply states that you cannot process user identifiable data when this is not needed. There should be a business necessity if you want to oblige this. The only option you have is to let employees opt-in voluntarily" (#12)<br>"We need to assess the law and regulations. I believe you need explicit consent when you want to use personal information" (#13)<br>"I think that you need to design the system in a way that you cannot map an employee and their location without them registering first" (#14) | The system needs employees' approval to start tracking them (opt-in) |
| "I think that the system needs to derive the status of a user based on their calendar/skype status" (#1)<br>"I think it is always easy, of course we also use Skype here, so you can easily just ask where they are. If someone is in a call, then it is easy to find track their location. So it is handy if you see their status already" (#5)<br>"Their Skype status shows if they are available. If someone is busy I won't approach him" (#8)<br>"A connection with your agenda to ensure that your workspace is nearby your meetings would be nice" (#8)<br>"You should have a connection with the company-system to link a person to a device" (#9)<br>"You should also anticipate on the future, for example that you can see where vacant parking spots are, and that your agenda is used to provide you with alternatives" (#13)<br>"I think more value can be gained over time if you make it scalable for other data to be considered as well" (#15) | The system is interoperable with other data sources (IM + Calendar) |
| "People will not enable something themselves, this need to happen automatically" (#1)<br>"I think it should happen automatically, because when you need to check in there is no immediate reward, the person you want to find needs to be checked in" (#2)<br>"People won't check-in or they will forget it. This needs to happen automatically" (#8)<br>"Checking in is not used by anyone" (#9)<br>"We encounter that when we offer apps, people are annoyed if they have to take some action themselves, like logging in" (#13) | The system is able to find IoT devices automatically |
| "I think it is better to determine the user's location via their laptop instead of their phone, because this infringes the privacy less. When I go to the bathroom I take my phone with me, and people don't need to know when / how long I am away" (#1)<br>"The laptop needs to be used, because your laptop is at the place where you work" (#2)<br>"I think that the laptop is better. You take your smartphone always with you, it doesn't determine your workplace" (#5)<br>"You're phone gives a more accurate representation of your location, however, I also take mine to the bathroom. The laptop is better, because this is at your workplace" (#8)<br>"I would not mind it at all that the location of my laptop is being tracked" (#9)<br>"I would have less concerns with sharing the location of my laptop" (#10) | The system determines the employee's location based on the location of their laptop |

| | |
|---|---|
| “I think people are less reluctant to show where their laptop is” (#14) | |
| “It can also be good to determine the location based on their smartphone – it often happens that I go to another floor for a coffee” (#4)<br>“I think the smartphone is better, as this really shows where you are, my laptop is not always with me in a meeting” (#16) | The system determines the employee’s location based on the location of their smartphone |
| “The data needs to be stored anonymously, so after the data request, the user cannot be identified anymore” (#3)<br>“I don’t like that historical data is stored on me” (#4)<br>“The bottleneck is privacy, what you can see of other and what you cannot see” (#9)<br>“I don’t want it to be like Big Brother, the data that I create should only be used for general purposes” (#10)<br>“I think that using personal data is challenging, privacy is a big issue!”(#14) | The systems collects and stores no user identifiable data |
| “On the one hand privacy is important for me, but on the other hand it seems very convenient to easily find someone” (#2)<br>“Perhaps data on user location can be stored for one hour only to perform analytics” (#3)<br>“Something like suggesting desks would be nice, based on your preferred ‘clusters’, colleagues you often sit with” (#3)<br>“Historical data needs to be saved somehow to be able to suggest desks” (#4)<br>“Ideally, you have a real-time overview of current occupation, but also historical data to e.g. create zones” (#6)<br>“If you want to find your colleagues, you inevitably need personal data, no way around that” (#15) | The system collects and stores user identifiable data |
| “The suggestions have to be done well and have a high accuracy, otherwise nobody will use it and the system dies” (#7)<br>“A platform is needed to ensure that real value is created, you want this to be done automatically, and in a good way” (#11)<br>“It is important that the system is easy-to-use, up-to-date, and accurate. If the system says that a room is available, it should indeed be available. There is nothing more frustrating than an occupied room when you expect it to be vacant” (#13)<br>“It takes some time to collect data and develop a good predictive model, you want this model to be trained well to be able to provide relevant suggestions” (#14)<br>“If the system is wrong a few times, people will perceive it as useless” (#16) | The system needs to have a high accuracy of suggestions |
| “You want users to use the system when they enter the building, so it needs to be real-time and quick” (#3)<br>“In the ideal situation this is real-time, so also based on the current occupation of desks” (#6)<br>“It should be easier than calling. For example a push notification if you walk in the building” (#8)<br>“You want it to be quick, you don’t want to wait for five minutes after you have put in a request” (#11)<br>“From a facility management perspective it is important to understand the real-time occupation” (#13)<br>“I think that fast analytics is needed, desks can become occupied so fast” (#15) | The system needs to be able to work in real-time |
| “Communication is very important as well, users need to know how the system works and what kind of data is collected on them” (#4)<br>“You have to explain what kind of data you collect very carefully, show them what you know about them” (#7)<br>“I think people can be convinced to use the system if you offer them more than just the location and explain this well” (#7)<br>“I think that people in our department would use such an app easily, but this does not have to be the case, it should be easy to use” (#11)<br>“It is important that the system is easy-to-use, up-to-date, and accurate” (#13)<br>“People need to understand how the analytics work, you don’t want a black box” (#15) | The systems needs to be easy to use and easy to understand |
| “Something like suggesting desks would be nice, based on your preferred ‘clusters’, colleagues you often sit with” (#3)<br>“Perhaps you should be able to make project teams. You give in the names of your team, and when you enter the building you get a notification with their location” (#6)<br>“It would be nice if I get a notification of where my team is sitting, to have a user profile in which I can give in preferences, like working in a quiet place” (#8)<br>“It is interesting if the system takes in my preferences” (#9)<br>“People have to feel that they have a say in the system. It can be that they want to have an outside view, sit in the sun, far away from a certain colleague… It would be nice to have suggestions and you can pick one” (#10) | The system allows employees to provide their preference for a workspace |

| | |
|---|---|
| "You can also search activity-based, for example I need a meeting room or lounge area; that can be options. You can also look at subject area, for example near someone with a specialization in tax or accountancy" (#13)<br>"People are all different, so you they need to remain in control and be able to overrule the suggestions" (#16) | |
| "You need to maintain the system and update, you cannot expect that it keeps working after you have designed and implemented it once" (#7)<br>"You need a platform that can scale well, and can be changed based on what you want to achieve" (#11)<br>"If new sensors are installed and data is in a different format, you need to be able to handle that without the system breaking" (#15) | The system needs to be updated with changes in requirements and technologies |
| "I can also imagine that this system is helpful for finding empty places in the canteen, or even in the parking garage" (#8)<br>"You talked about the smart city, I think that in 10 years this use case will be so common, as well as other use cases" (#16) | The system supports other use cases that are added |
| "People are sometimes also required to sit apart, e.g. based on the function they are working it. The system should take this into account" (#7)<br>"Certain departments always sit in the same floor, this should be handled as well" (#9)<br>"Perhaps not everyone has a smartphone, then you need to have a console in a shared space that people can use to find a workspace or their colleague" (#10)<br>"As facility management we sometimes redesign some areas, this should be possible" (#16) | The system supports specific constraints of the tenant |
| "I should be able to 'turn off' a workspace, when something is broken, e.g. a chair or screen" (#9)<br>"From a facility management perspective it is important to understand the real-time occupation. I need to use those insights to make decisions when needed" (#13)<br>"If I want to make reports, I need all the data, also historical data, but you should be cautious with providing access to this data as it is quite sensitive" (#15) | The system supports various user permissions for the system |

In total, 16 requirements have been found from the interviews in round 1, see the table below. In the first column, the Req.ID is displayed. In the second column the requirements, and in the third column the requirement type.

| Req.ID | Requirement | Requirement type |
|---|---|---|
| 1. | The system enables employees to disable tracking (opt-out) | Functional |
| 2. | The system needs employees' approval to start tracking them (opt-in) | Functional |
| 3. | The system is interoperable with other data sources (IM + Calendar) | Design Constraint |
| 4. | The system is able to find IoT devices automatically | Functional |
| 5. | The system determines the u employee's location based on the location of their laptop | Functional |
| 6. | The system determines the employee's location based on the location of their smartphone | Functional |
| 7. | The systems collects and stores no user identifiable data | Functional |
| 8. | The system collects and stores user identifiable data | Functional |
| 9. | The system needs to have a high accuracy of suggestions | Non-functional |
| 10. | The system needs to be able to work in real-time | Functional |
| 11. | The systems needs to be easy to use and easy to understand | Non-functional |
| 12. | The system allows employees to provide their preference for a workspace | Functional |
| 13. | The system needs to be updated with changes in requirements and technologies | Non-functional |
| 14. | The system supports other use cases that are added | Design constraint |
| 15. | The system supports specific constraints of the tenant | Design constraint |
| 16. | The system supports various user permissions for the system | Functional / General |

**Prioritization of open questions**

1. *The system enables employees to disable tracking (opt-out)*

This requirement is stated multiple times, especially by employees, but also by other respondents. They want to be able to stop the system from tracking them, either temporarily, or for always. This is even stated to be required by law when personal data is being collected. Therefore, this requirement will be prioritized as **high**.

2. *The system needs employees' approval to start tracking them (opt-in)*

As with the first requirement, most respondents state that a solution like this should not be forced and that employees need to explicitly opt-in in order to start tracking their location. The privacy officer even states that this is required by law when there is no business necessity. Therefore, this requirement will be prioritized as **high**.

3. *The system is interoperable with other data sources (IM + Calendar)*

This requirement is stated by multiple stakeholder-groups, but especially by employees. They argue that it would be 'nice' if the status of an employee that is provided by an IM-client (e.g. available/busy/do not disturb) is also displayed when that employee is searched for, this way people are able to indicate whether they are open for conversation, or trying to work quietly. Also other data sources, as the employee's agenda are mentioned, because this can provide additional information as well. No real necessity emerged during the interviews, but it was still mentioned quite often, therefore this requirement will be prioritized as **medium**.

4. *The system is able to find IoT devices automatically*

This requirement indicates that no user action is needed before they can be found, or before desks are stated as vacant. As an example, checking in at a desk and letting others know that you sit at that desk is not preferred, this is seen as annoying and people will forget it. A high user adoption is needed to let this solution work, there is no value if only 10 people use it, and therefore this requirement will be prioritized as **high**.

5. *The system determines the u employee's location based on the location of their laptop*

This requirement emerged as employees were asked how they would prefer to be tracked – either by their smartphone or by their laptop. Most stakeholders argued that the location of their laptop indicates their 'real' working place, their smartphone is also carried around when they go to the bathroom or for a coffee break – this does not need to be shared. By taking the location of their laptop as a proxy for their actual location, employees state to be more willing to enable this. Therefore, this requirement will be prioritized as **high**.

6. *The system determines the employee's location based on the location of their smartphone*

This requirement is very much related to Req. 5. Determining an employee's location based on their laptop is seen as less intrusive, only a small number of respondents preferred their smartphone location to be tracked. Therefore, this requirement will be prioritized as **low**.

7. *The systems collects and stores no user identifiable data*

This requirement is clearly conflicting with the business goal, in which is stated that users are able to find the location of their colleagues. Inherent to this use case is that user identifiable data is collected (and stored in order to base suggestions on this data). Concerns that were raised are mainly related to the fact that data is collected without their consent, and, as will be explained in Req. 8 and Req. 9, people understand that this data is needed for the use case and to improve the accuracy of suggestions. Therefore, this requirement will be prioritized as **low**.

*8. The system collects and stores user identifiable data*

As discussed in Req. 7, the respondents understand that collecting user identifiable data is needed for the tracking of employees, and storing this data to provide relevant suggestions. Data scientists have offered ideas to reduce the amount of data that needs to be stored; it is argued that storing this data only for a limited time will be enough to create 'clusters', these clusters can consequently be used to provide suggestions regarding workspaces. Therefore, this requirement will be prioritized as **high**.

*9. The system needs to have a high accuracy of suggestions*

This requirement is stated to be important, as a low accuracy of suggestions (e.g. a workspace that is not preferred, or a desk/meeting room that is already occupied) can be disastrous for the solution. If people cannot rely on the suggestions, the system will 'die'. Therefore, this requirement will be prioritized as **high**.

*10. The system needs to be able to work in real-time*

As with Reg. 9, respondents state that the suggestions should be based on the real-time situation. Some respondents even stated that a push notification should be provided if you enter the building. People don't want to wait for five minutes before they receive an answer back. Therefore, this requirement will be prioritized as **high**.

*11. The systems needs to be easy to use and easy to understand*

This requirement is stated to be important for people to use the system, and share their data. If it is unclear what kind of data is collected exactly, and how this data is being used, people are more reluctant to share their data. Communication is important, and the application should be easy to use, also by people how are less tech-savvy. Therefore, this requirement will be prioritized as **high**.

*12. The system allows employees to provide their preference for a workspace*

This requirement is often stated by various stakeholders. It is argued that people want to have a say in the system, e.g. by providing various suggestions and letting the user pick one. People might prefer a desk nearby their colleagues, or e.g. in a quiet area. Therefore, this requirement will be prioritized as **high**.

*13. The system needs to be updated with changes in requirements and technologies*

This requirement is stated to indicate the technical nature of this solution, as technologies can change, as well as requirements for the system. This is however not mentioned very much by the respondents, therefore, this requirement will be prioritized as **medium**.

*14. The system supports other use cases that are added*

This requirement is stated as other use cases for workspace optimization were mentioned by the respondents. An employee would like to see more optimized parking in the garage, and more optimized use of the canteen, where it is sometimes very busy. Due to the little mention of this requirement, it will be prioritized as **low**.

*15. The system supports specific constraints of the tenant*

During the interview became clear that the building also has some tenant-specific requirements. As an example is given that some departments need to sit on a certain floor, in order to prevent leaks: 'Chinese walls'. Also, not everyone might have a smartphone for some tenants, this means that specific constraints can be placed on the system. As this is not directly important for the general architecture, this requirement will be prioritized as **medium**.

*16. The system supports various user permissions for the system*

This requirement indicates that the system allows different roles, e.g. facility management desires to 'disable' a certain desk when it cannot be used. This requirement is stated to be important for the accuracy of suggestions; being suggested a desk that cannot be used reduces employee's trust in the system. Therefore, this requirement will be prioritized as **high**.

### Closed questions

For the closed questions, the stakeholder's scores are weighted over the inverse of the size of the stakeholder group, thus, smaller groups have a higher weight. The group sizes are displayed in the table below.

| Stakeholder | Group size |
|---|---|
| Employee | 5 |
| Data scientist | 4 |
| Facility manager | 4 |
| Information systems manager | 2 |
| Privacy officer | 1 |

The following table displays the answers of the stakeholders on the first 10 questions.

| Resp. | Stakeholder | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Employee | 4 | 3 | 2 | 5 | 5 | 1 | 4 | 3 | 1 | 4 |
| 2 | Employee | 3 | 3 | 4 | 4 | 4 | 3 | 4 | 3 | 4 | 5 |
| 3 | Data scientist | 3 | 3 | 4 | 4 | 5 | 5 | 3 | 4 | 4 | 5 |
| 4 | Employee | 4 | 3 | 4 | 5 | 5 | 4 | 1 | 2 | 2 | 5 |
| 5 | Employee | 3 | 4 | 4 | 4 | 5 | 4 | 1 | 2 | 5 | 4 |
| 6 | Data scientist | 3 | 4 | 2 | 2 | 5 | 4 | 1 | 3 | 5 | 1 |
| 7 | Facility manager | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 4 | 3 | 4 |
| 8 | Employee | 5 | 3 | 3 | 3 | 5 | 2 | 5 | 4 | 2 | 4 |
| 9 | Facility manager | 5 | 2 | 2 | 3 | 4 | 1 | 4 | 3 | 4 | 2 |
| 10 | Information systems manager | 2 | 1 | 5 | 5 | 4 | 1 | 5 | 1 | 1 | 5 |
| 11 | Information systems manager | 5 | 4 | 3 | 4 | 4 | 4 | 4 | 1 | 3 | 4 |
| 12 | Privacy officer | 4 | 1 | 5 | 5 | 5 | 1 | 4 | 4 | 1 | 5 |
| 13 | Facility manager | 5 | 4 | 4 | 4 | 5 | 4 | 3 | 4 | 3 | 4 |
| 14 | Data scientist | 4 | 3 | 4 | 3 | 5 | 4 | 5 | 5 | 2 | 5 |
| 15 | Data scientist | 2 | 3 | 2 | 5 | 5 | 2 | 5 | 2 | 5 | 5 |
| 16 | Facility manager | 5 | 4 | 3 | 4 | 5 | 4 | 5 | 4 | 4 | 5 |

The following table displays the weighted answers of the stakeholders on the first 10 questions. The weights are based on the stakeholder group size.

| Resp. | Stakeholder | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Employee | 0,8 | 0,6 | 0,4 | 1,0 | 1,0 | 0,2 | 0,8 | 0,6 | 0,2 | 0,8 |
| 2 | Employee | 0,6 | 0,6 | 0,8 | 0,8 | 0,8 | 0,6 | 0,8 | 0,6 | 0,8 | 0,6 |
| 3 | Data scientist | 1,5 | 1,5 | 2,0 | 2,0 | 2,5 | 2,5 | 1,5 | 2,0 | 2,0 | 1,5 |
| 4 | Employee | 0,8 | 0,6 | 0,8 | 1,0 | 1,0 | 0,8 | 0,2 | 0,4 | 0,4 | 0,8 |
| 5 | Employee | 0,6 | 0,8 | 0,8 | 0,8 | 1,0 | 0,8 | 0,2 | 0,4 | 1,0 | 0,6 |
| 6 | Data scientist | 1,5 | 2,0 | 1,0 | 1,0 | 2,5 | 2,0 | 0,5 | 1,5 | 2,5 | 1,5 |
| 7 | Facility manager | 1,3 | 1,3 | 1,7 | 1,7 | 1,7 | 1,7 | 1,7 | 1,3 | 1,0 | 1,3 |
| 8 | Employee | 1,0 | 0,6 | 0,6 | 0,6 | 1,0 | 0,4 | 1,0 | 0,8 | 0,4 | 1,0 |
| 9 | Facility manager | 1,7 | 0,7 | 0,7 | 1,0 | 1,3 | 0,3 | 1,3 | 1,0 | 1,3 | 1,7 |
| 10 | Information systems manager | 1,0 | 0,5 | 2,5 | 2,5 | 2,0 | 0,5 | 2,5 | 0,5 | 0,5 | 1,0 |
| 11 | Information systems manager | 2,5 | 2,0 | 1,5 | 2,0 | 2,0 | 2,0 | 2,0 | 0,5 | 1,5 | 2,5 |
| 12 | Privacy officer | 4,0 | 1,0 | 5,0 | 5,0 | 5,0 | 1,0 | 4,0 | 4,0 | 1,0 | 4,0 |
| 13 | Facility manager | 1,7 | 1,3 | 1,3 | 1,3 | 1,7 | 1,3 | 1,0 | 1,3 | 1,0 | 1,7 |
| 14 | Data scientist | 1.0 | 0.8 | 1.0 | 0.8 | 1.3 | 1.0 | 1.3 | 1.3 | 0.5 | 1.3 |
| 15 | Data scientist | 0.5 | 0.8 | 0.5 | 1.3 | 1.3 | 0.5 | 1.3 | 0.5 | 1.3 | 1.3 |
| 16 | Data scientist | 1.3 | 1.0 | 0.8 | 1.0 | 1.3 | 1.0 | 1.3 | 1.0 | 1.0 | 1.3 |

The weighted means can be calculated by taking the sum of the weighted scores, and dividing that by the number of stakeholder groups. The following table is the result of this process:

| Question | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Weighted mean** | **3.8** | **2.7** | **3.8** | **4.2** | **4.7** | **2.7** | **3.9** | **3.0** | **2.7** | **4.3** |
| **Priority** | **High** | **Med** | **High** | **High** | **High** | **Med** | **High** | **Med** | **Med** | **High** |

Finally, the weighted means are translated into priorities of the requirements. This is done according to the following scale, in which scores correspond with a priority. The priorities are added to the table above.


For question 11, in which qualities of the system are compared, the respondents are asked to rank 4 qualities that were related to IoT-A’s architectural perspectives. The most important quality was rated with 1, and the least important quality with 4. Again, the ranks are weighted for the size of stakeholder groups. The scores that are obtained and the corresponding priority are presented in the table below:

| Security & Privacy | Availability & Resilience | Evolution & Interoperability | Performance & Scalability |
|---|---|---|---|
| **1,9** | **2,5** | **2,5** | **3,0** |
| **High** | **Medium** | **Medium** | **Low** |

At last, the priorities are added to the final list of Unified requirements in Appendix D.

## Appendix D: Requirements

### *D1: Requirements following from the unified requirements*

| UNI ID | Description | Fit Criterion | Requirement Type | Conflicting | Priority |
|---|---|---|---|---|---|
| UNI.001 | Users are able to use the service anonymously | It is possible for a user to use the system without having any Personally Identifiable Information being tracked | Non-functional | | High |
| UNI.002 | Users have control how their data is exposed to other users | The system lets users select which personal data is accessible to other users | Non-functional | | High |
| UNI.005 | The system supports event-based, periodic and/or autonomous communication | The considered system must be able to use or combine event-based, periodic and autonomic communication | Functional | | High |
| UNI.010 | The devices/services in the system are able to collaborate for a certain task | Using the ARM it is possible to build a system that features autonomous collaboration between devices or services | Non-functional | | Medium |
| UNI.012 | The system is able to handle interference between IoT devices (avoidance and detection) | Error Detection and Correction FC is able to cope with radio interferences | Non-functional | | Medium |
| UNI.016 | The system supports physical entity location tracking (logical location) | It is possible to track a physical entity location | Functional | | High |
| UNI.018 | The system supports capabilities for data management (integration & storage, processing & analytics) | Using the ARM, it should be possible to select where and what kind of data processing should be performed | Functional | | High |
| UNI.041 | The system provides historical information about the physical entity | There exists a system component that allows for retrieval of historical information | Functional | Req. 7 | Medium |
| UNI.047 | The system ensures interoperability between objects or between applications | It is possible to exchange information between any two service or application (VE, IoT Service, application), provided they are granted access to each other | Non-functional | | Medium |
| UNI.050 | The system supports mobile physical entities | Physical mobility of physical entities is handled and reflected in the system | Non-functional | | High |
| UNI.058 | The system provides high availability | The system provides an agreed upon level of availability, e.g. by providing mechanisms to recover from component failures | Non-functional | | Medium |
| UNI.062 | The system provides trusted and secure communication and information management | Information is available and securely communicated | Design constraints | | High |
| UNI.065 | The system provides reliable services | The system provides services with an agreed upon level of reliability | Non-functional | | Medium |
| UNI.066 | The system provides integrity validation of virtual entities, devices, resources, and services | Tampered virtual entities, devices, resources, and services are rejected by the system | Functional | | Low |
| UNI.067 | The system provides different access permissions to information | The system implements and enforces different permission levels for access to information | Functional | | High |
| UNI.093 | The system shall be extensible for future technologies. | Widespread standards are used where possible | Non-functional | | Medium |
| UNI.099 | The system guarantees correctness of resolutions | Under proper conditions, the resolution functionality can guarantee correctness of their results | Non-functional | | Low |

| | | | | | |
|---|---|---|---|---|---|
| UNI.102 | The system takes external computing resources into account, e.g. 'the cloud'. | The system includes mechanisms that allow for the integration of external computing resources. | Non-functional | | Medium |
| UNI.252 | The service organization shall provide feedback within a reasonable amount of time. | A service orchestration component is implemented. | Non-functional | | Low |
| UNI.410 | The system restricts who can update and delete Digital Entity history | The feature is incorporated in the system | Functional | | High |
| UNI.411 | The system offers a unique identification of clients requesting data via the discovery / lookup services | The system contains unique identifier of clients | Functional | | Medium |
| UNI.414 | The system enables the dynamic discovery of virtual entities and their services | The system contains discovery function with the specification of the virtual entity and the specification of the required service as parameters | Functional | | High |
| UNI.423 | When performing discovery, resolution or lookup, the system must respect any aspect of privacy, including the possibility to retrieve information about or related to people. In addition some services should be accessible in an anonymous way, while others might require an explicit authentication or authorization of the user. | Pseudomized identifiers are unlinkable to other identifiers or a specific user | Functional | Req. 7 | High |
| UNI.502 | The system prevents a device from being activated without the consent of the owner. | A validation by the owner must be performed before their devices can be read | Non-functional | | High |
| UNI.503 | The system makes it be possible to change the owner of a device | Devices can change ownership, the system must incorporate this | Functional | | High |
| UNI.504 | The system prevents tracking of the identifier of the device by unauthorized entities. | The owner needs to authorize that a certain entity is able to track the device | Non-functional | | High |
| UNI.506 | The system supports communication across devices by aid of standardized communication interfaces. | The interfaces must be either standard ones or new ones that must be standardized | Design Constraint | | High |
| UNI.606 | The system makes the traceability of digital activities impossible | The system supports non-traceability of subjects | Non-functional | | High |
| UNI.714 | The system management shall pay attention to device constraints such as energy and memory | The system management is aware of device constraints such as energy and memory and takes this into account | Non-functional | | Low |
| UNI.715 | The system performs data collection on its current state | The system performs data collection on its current state | Functional | | Medium |

### Mapping of UNIs to interview questions round 1

| Q. | Unified requirement (UNIs) | Question | Unified requirement (UNIs) |
|---|---|---|---|
| **1** | <no specific UNIs – validate business goal> | **8** | UNI.102 |
| **2** | <no specific UNIs – validate business goal> | **9** | UNI.411 |
| **3** | UNI.001, UNI.606 | **10** | UNI.423, UNI.502, UNI.504 |
| **4** | UNI.002 | **11:** Security & Privacy | UNI.001, UNI.002, UNI.062, |
| **5** | UNI.005 | **11:** Availability & resilience | UNI.058, UNI.065, |
| **6** | UNI.041, UNI.715 | **11:** Evolution & interoperability | UNI.012, UNI.047, UNI.093 |
| **7** | UNI.067, UNI.410 | **11:** Performance & scalability | UNI.099, UNI.252, UNI.066, UNI.714 |

*D2: Requirements collected through interviews*

| Req.ID | Description | Fit criterion | Requirement type | Conflicting | Stakeholder | Priority |
|---|---|---|---|---|---|---|
| 1. | The system enables employees to disable tracking (opt-out) | A list of employees that can be tracked is taken into account | Functional | Req. 2 | Multiple | High |
| 2. | The system needs employees' approval to start tracking them (opt-in) | A list of employees that can be tracked is taken into account | Functional | Req. 1 | Multiple | High |
| 3. | The system is interoperable with other data sources (IM + Calendar) | IM and calendar are part of the system | Design Constraint | | Multiple | Medium |
| 4. | The system is able to find IoT devices automatically | Devices can be found without adding them on beforehand | Non-functional | Req. 2 | Multiple | High |
| 5. | The system determines the employee's location based on the location of their laptop | The laptop is a physical entity that is tracked | Functional | Req. 6 | Multiple | High |
| 6. | The system determines the employee's location based on the location of their smartphone | The smartphone is a physical entity that is tracked | Functional | Req. 5 | Multiple | Low |
| 7. | The systems collects and stores no user identifiable data | No user identifiable information is collected and stored | Non-functional | Req. 8 + business goals | Multiple | Low |
| 8. | The system collects and stores user identifiable data | User identifiable information is collected and stored | Non-functional | Req. 7 | Data scientist | High |
| 9. | The system needs to have a high accuracy of suggestions | Suggestions are often followed | Non-functional | | Multiple | High |
| 10. | The system needs to be able to work in real-time | The system is able to process real-time data and offer real-time suggestions | Non-functional | | Multiple | High |
| 11. | The systems needs to be easy to use and easy to understand | The system is user friendly and no 'black box' | Non-functional | | Information systems manager | High |
| 12. | The system allows employees to provide their preference for a workspace | The system takes user preferences into account | Functional | | Employee | High |
| 13. | The system needs to be updated with changes in requirements and technologies | Widespread standards are used where possible | Non-functional | | Multiple | Medium |
| 14. | The system supports other use cases that are added | The system is built modularly and is extendable | Design constraint | | Employee | Low |
| 15. | The system supports specific constraints of the tenant | The system is built modularly and allows additional constraints | Design constraint | | Facility management | Medium |
| 16. | The system supports various user permissions for the system | The system makes a distinction between user types with varying permissions | Functional | | Facility management | High |

# Appendix E: Architecture evaluation

***E1: Interview guide round 2***

**Introduction**

This interview concerns *workspace optimization in smart buildings* through IoT sensors. The use cases are:

- Finding vacant desks and meeting rooms in the building
- Finding the location of colleagues in the building

Through a smartphone application, the user is able to see vacant desks and meeting rooms, find the location of their colleagues, and see suggestions for desks (workspace optimization).

This data is collected through: WiFi Access points, desk sensors, and motion detectors in rooms.

**Explanation of architectures**

IoT-A is used as a reference architecture for the development of the proposed architecture. Requirements for the architecture are collected through interviews with relevant stakeholders. The architectures that are developed are displayed in figure X and figure X.

**Questions**

1. Are you familiar with the IoT ARM (IoT-A) reference architecture?
2. How effective do you consider this proposed architecture for solving the problem as described?
3. How feasible do you consider the proposed architecture regarding deployment in a smart building?
4. Do you consider the architectural views to be consistent?
5. Do you consider the architectural notation to be correct?
6. Do you consider the proposed architecture to be interoperable with other IoT architectures?
7. Do you consider the information provided in the proposed architecture and documentation to be sufficient?
8. Do you consider a clear focus on data capabilities (integration, processing & analytics) in this proposed architecture?
9. Where do you see potential for future extension in this proposed architecture?

**Fulfilment of requirements**

These questions are related to the fulfilment of requirements that were stated for the architecture design. In particular requirements with a high priority need to be fulfilled in the proposed architecture.

An overview of these requirements is presented here, please indicate whether you believe this requirements has been fulfilled by placing an 'X' in the fourth column.

| UNI ID | Description | Fit Criterion | Fulfilled? |
|---|---|---|---|
| UNI.001 | Users are able to use the service anonymously | It is possible for a user to use the system without having any Personally Identifiable Information being tracked | |
| UNI.002 | Users have control how their data is exposed to other users | The system lets users select which personal data is accessible to other users | |
| UNI.005 | The system supports event-based, periodic and/or autonomous communication | The considered system must be able to use or combine event-based, periodic and autonomic communication | |
| UNI.016 | The system supports physical entity location tracking (logical location) | It is possible to track a physical entity location | |

| | | | |
|---|---|---|---|
| UNI.018 | The system supports data capabilities (integration, processing and analysis) | Using the ARM, it should be possible to select where and what kind of data processing should be performed | |
| UNI.050 | The system supports mobile physical entities | Physical mobility of physical entities is handled and reflected in the system | |
| UNI.062 | The system provides trusted and secure communication and information management | Information is available and securely communicated | |
| UNI.067 | The system provides different access permissions to information | The system implements and enforces different permission levels for access to information | |
| UNI.410 | The system restricts who can update and delete Digital Entity history | The feature is incorporated in the system | |
| UNI.414 | The system enables the dynamic discovery of virtual entities and their services | The system contains discovery function with the specification of the virtual entity and the specification of the required service as parameters | |
| UNI.423 | When performing discovery, resolution or lookup, the system must respect any aspect of privacy, including the possibility to retrieve information about or related to people. In addition some services should be accessible in an anonymous way, while others might require an explicit authentication or authorization of the user. | Pseudomized identifiers are unlinkable to other identifiers or a specific user | |
| UNI.502 | The system prevents a device from being activated without the consent of the owner. | A validation by the owner must be performed before their devices can be read | |
| UNI.503 | The system makes it be possible to change the owner of a device | Devices can change ownership, the system must incorporate this | |
| UNI.504 | The system prevents tracking of the identifier of the device by unauthorized entities. | The owner needs to authorize that a certain entity is able to track the device | |
| UNI.506 | The system supports communication across devices by aid of standardized communication interfaces. | The SW interfaces on the GW must be either standard ones or new that must be standardized | |
| UNI.606 | The system makes the traceability of digital activities impossible | The system supports non-traceability of subjects | |
| 1. | The system enables employees to disable tracking (opt-out) | A list of employees that can be tracked is taken into account | |
| 2 | The system needs employees' approval to start tracking them (opt-in) | A list of employees that can be tracked is taken into account | |
| 4. | The system is able to find IoT devices automatically | Devices can be found without adding them on beforehand | |
| 5. | The system determines the employee's location based on the location of their laptop | The laptop is a physical entity that is tracked | |
| 8. | The system collects and stores user identifiable data | User identifiable information is collected and stored | |
| 9. | The system needs to have a high accuracy of suggestions | Suggestions are often followed | |
| 10. | The system needs to be able to work in real-time | The system is able to process real-time data and offer real-time suggestions | |
| 11. | The systems needs to be easy to use and easy to understand | The system is user friendly and no 'black box' | |
| 12. | The system allows employees to provide their preference for a workspace | The system takes user preferences into account | |
| 16. | The system supports various user permissions for the system | The system makes a distinction between user types with varying permissions | |

***E2: Interview findings round 2***

| UNI ID | Expert 1 | Expert 2 |
|---|---|---|
| UNI.001 | | |
| UNI.002 | X | X |
| UNI.005 | X | X |
| UNI.016 | X | X |
| UNI.018 | X | X |
| UNI.050 | X | X |
| UNI.062 | X | X |
| UNI.067 | X | X |
| UNI.410 | X | X |
| UNI.414 | X | X |
| UNI.423 | X | X |
| UNI.502 | X | X |
| UNI.503 | X | |
| UNI.504 | | |
| UNI.506 | X | X |
| UNI.606 | X | X |

| UNI ID | Expert 1 | Expert 2 |
|---|---|---|
| 1. | X | X |
| 2. | X | X |
| 4. | X | |
| 5. | X | X |
| 8. | X | X |
| 9. | | |
| 10. | X | X |
| 11. | | |
| 12. | X | X |
| 16. | X | X |

Two IoT Architects are asked to look at the list of requirements that is used to design the architectural views, and to indicate whether they consider the requirements to be fulfilled in these views. The experts were interviewed individually in two separate sessions, so the findings, which are presented in the table above, are a combination of both their findings.

After discussing their findings, the following becomes clear. First of all, the experts are mostly in agreement whether the requirements are (un)fulfilled. Further, the requirements that are rated as unfulfilled are mostly *non-functional requirements*. These experts agree that, as they describe qualities of the system, it can be difficult to represent them in the architectural views. The following requirements are found to be lacking by both experts:

*UNI.001: Users are able to use the service anonymously*
This requirement is (partially) unfulfilled on purpose, as explicit permission of users is needed to track them throughout the building. To stimulate employee opt-ins, employees are only able to use the system when they sign up first, therefore, users of the service are known. However, no data is stored about the queries these employees do, e.g. which colleague location is requested.

*UNI.054: The system prevents tracking of the identifier of the device by unauthorized entities*
This requirement is related to the overall (data) security of the IoT solution. In the Functional View is described that the *Privacy and Security FG* handles this by e.g. restricting access to unauthorized entities. However, the security of the organizations IT system needs to be in in order, because when that system is e.g. hacked, unauthorized entities might be able to access the data of this IoT system. As the experts rate this to be unfulfilled, this needs to be explained better in the documentation.

*Req.ID 9: The system needs to have a high accuracy of suggestions*
This requirements is rated as unfulfilled by both experts, because the solution has not been demonstrated. The accuracy can only be determined after the system has been deployed fully, therefore this rating was expected.

*Req.ID 11: The systems needs to be easy to use and easy to understand*
As with Req.ID 9, the experts state that a working example of the system, and perhaps a separate study on ‘user satisfaction/perception’ is needed to determine whether users perceive the system as easy-to-use and understand.

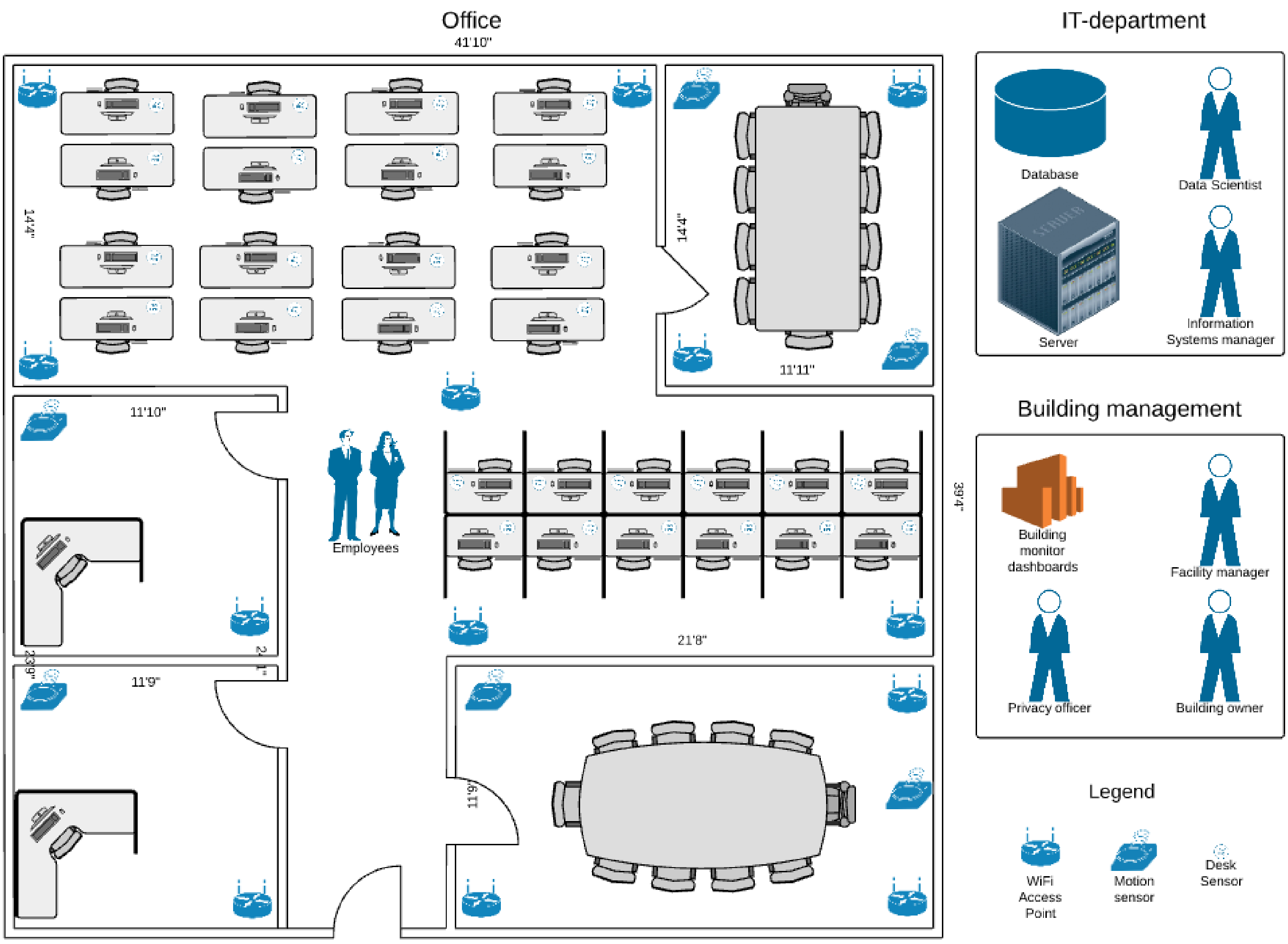
At last, some requirements were found to be lacking by only one expert.

*UNI.503: The system makes it be possible to change the owner of a device*
One IoT Architect states that this requirement is not fulfilled in his opinion, as it is not clear how it works when a device changes ownership. The design choice regarding this is to create a mapping between a device's MAC-address and the employee's ID is stored in the *WhitelistDB*. When the devices changes ownership, the information in this database can be updated. This will be explained more thoroughly in the documentation.

*Req.ID 4: The system is able to find IoT devices automatically*
One IoT Architect rates this requirement as unfulfilled, which is mostly true. In the system, new IoT devices (e.g. a new desk sensor) need to be added to the system and configured, as the sensor needs to be linked to a physical desk. This happens mostly in the *Member FC*, which is part of the *Management FG*.

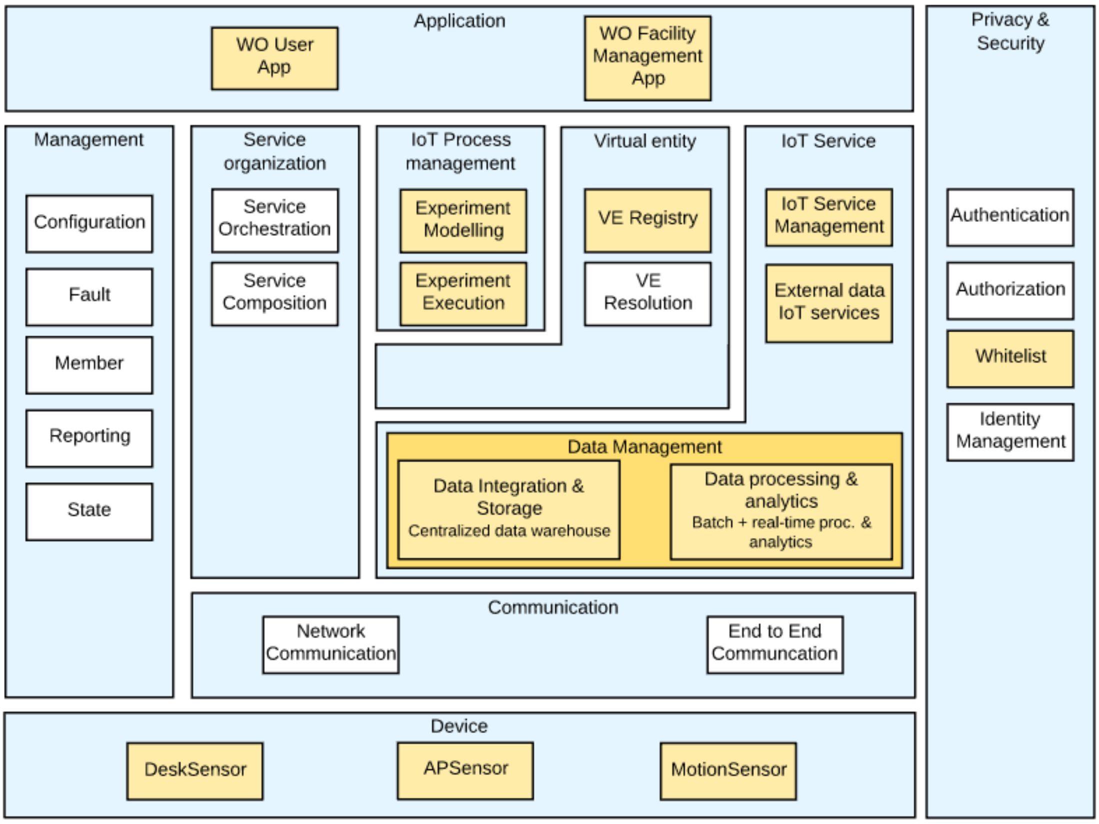
## Appendix F: Final Architecture

### *F1: IoT Context View*



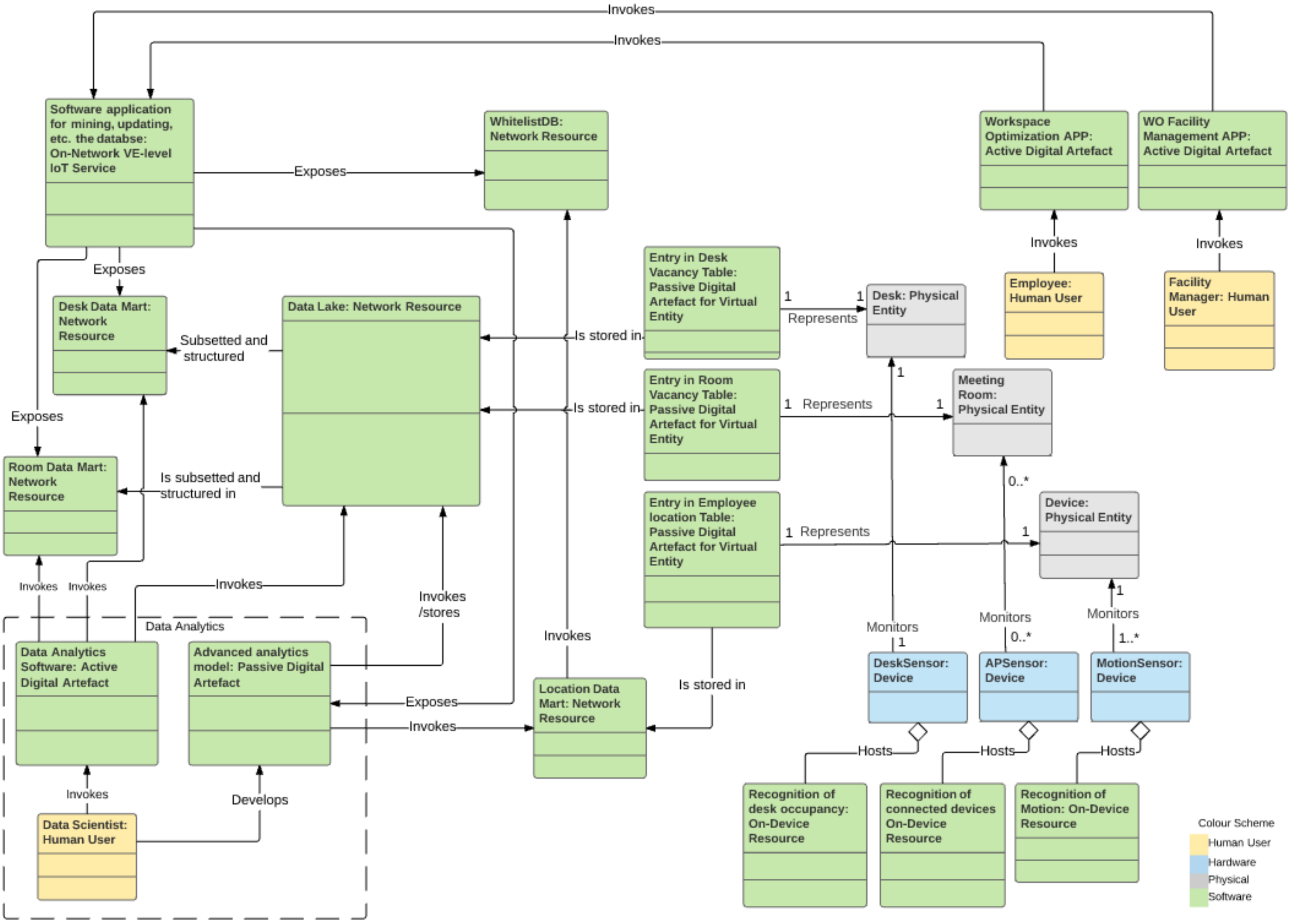

An explanation of the Context View is provided in section 7.2

***F2: Functional View***




A detailed explanation of the Functional View is provided in section 7.4

*F3: Information View*




The following design choices are applied in the Information View:
When employees *opt-in* to the system, their registration is stored in the *WhitelistDB*. This database consists of an EmployeeID and the MAC-address of their device. All other (raw) data that is collected through sensors is integrated and stored in a *data lake*. Subsets of this data for a specific purpose is stored in data marts for easy retrieval, e.g. data marts for *Desks* and *Rooms* and *Location* (of employees). The *Location data mart* consists of entries of WiFi Access Points and the MAC-addresses of devices that are connected to this Access Point. Due to this setup, only MAC-addresses of employees that did opt-in can be linked to a location in the building, this preserves the privacy of employees that did not register.

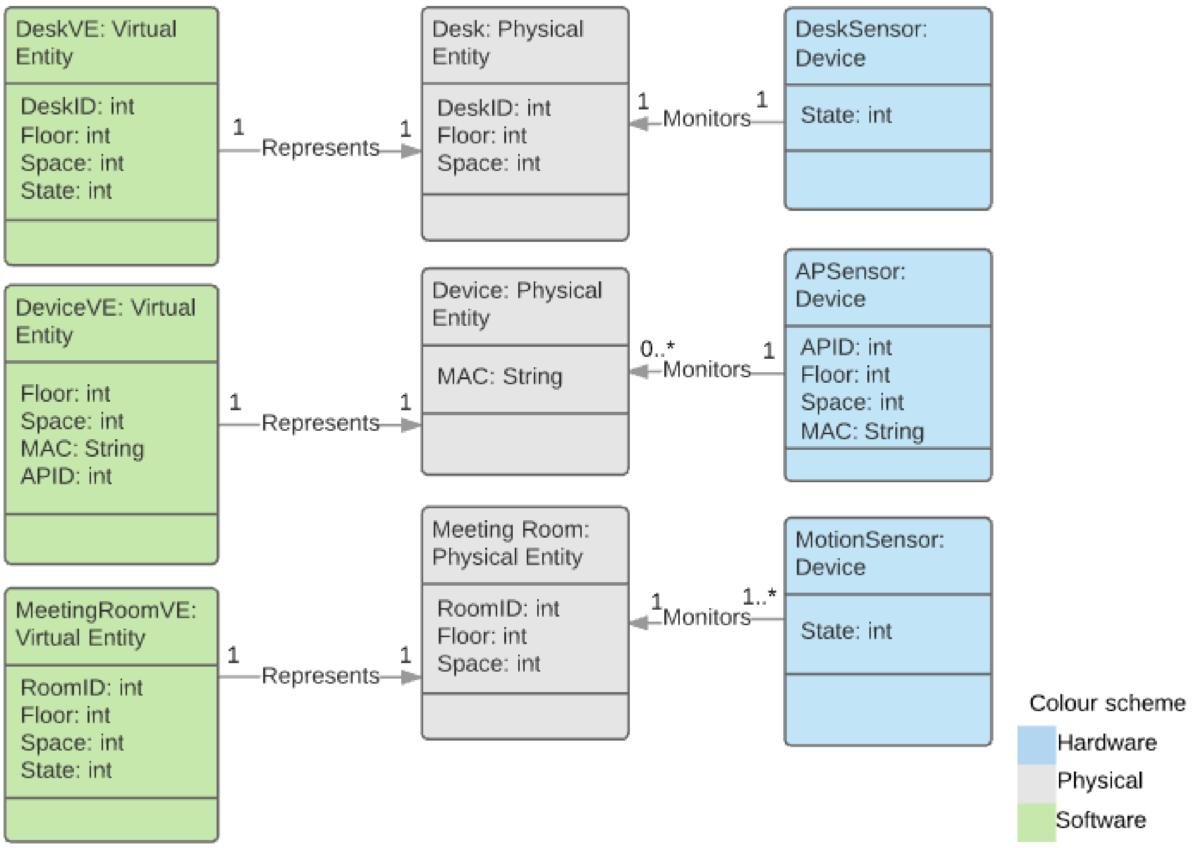
Data processing & analytics are also performed in a centralized way, through a combination of both batch processing and real-time processing. Batch processing is used to perform (advanced) analytics on the *location data mart*, as well as on the data in the data lake. Analytics on the *Location data mart* are mainly performed to derive 'clusters' of employees that often sit together, these insights are stored in the data lake and are used to suggest workspaces. Each week, the *Location data mart* is flushed; as the analytics are already performed, there is no need to store this data any longer.

Real-time analytics are used to analyse the *Desk data mart* and *Room data mart*, as a real-time occupancy-status is needed. When an employee requests suggestions for a workspace nearby colleagues, these suggestions are retrieved in real-time by combining data sources as follows:

- Real-time occupancy of desks to find a vacant desk
- Suitable workspace nearby colleagues by looking at his ‘cluster’ (of colleagues he often sits with), and where this ‘cluster’ is seated in the building.

Analytics on the total data lake are also used for the creation of e.g. a dashboard that provides usage statistics to facility management.

***F4: Physical-Entity View***




A detailed description of the Physical-Entity View is provided in section 7.1

# Appendix G: Scientific Article

*Scientific article for a master thesis Systems Engineering, Policy Analysis and Management (SEPAM) at the Delft University of Technology.*

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# Integrating Data Management capabilities in Internet of Things Reference Architectures

## Case study for workspace optimization in smart buildings


## Abstract

A lack of capabilities for data management (data integration, storage, processing & analytics) in Internet of Things (IoT) solutions, as well as non-interoperability between these solutions are two existing challenges for realizing the IoT vision. Reference architectures are being developed to improve interoperability between solutions, but even these reference architectures seem to be lacking integration of data management. Therefore, questions emerge on how to integrate these capabilities for data management in IoT solutions. This paper presents a study in which an IoT architecture is designed for workspace optimization in smart buildings, with an integration of capabilities for data management. The architecture has been designed through an empirical study in which requirements are collected through interviews with relevant stakeholders, as well as experts to validate the architecture. Findings from this study result in a proposed extension for the reference architecture that is used (IoT-A) that integrates data management as part of the important functionalities for the system.


## I. Introduction

The Internet of Things (IoT) has grown enormously in recent years. Even though the field is maturing, various challenges still exist (Gubbi et al., 2013). Non-interoperability of IoT solutions is one of the challenges that is mentioned. As IoT solutions are mainly being developed with a narrow scope by a variety companies, standardization efforts are fragmented (Lilis et al., 2017). Another challenge is a lack of capabilities for data management in IoT systems: a clear approach to manage the data that is being collected and to gain value from this data is missing, whereas this needs to be integrated from the systems design already (Noronha et al., 2014; Zdravkovi et al., 2016)

In order to improve interoperability between IoT solutions, various IoT reference architectures have been or are currently being developed to structure the design and development of IoT systems by defining e.g. common guidelines and building blocks (Cavalcante et al., 2015; Weyrich & Ebert, 2016). However, recent research suggests that the integration of capabilities for data management (integration, storage, processing, and analytics) in these reference architectures are mostly only partially fulfilled, or not fulfilled at all. This has consequences for the value that is attained from these IoT solutions (Cavalcante et al., 2015; Noronha et al., 2014)

Therefore, the following questions emerges: How can capabilities for data management be incorporated in interoperable IoT Architectures?

Finding an answer to this question is important for IoT development, as interoperable architectures are needed to create connected solutions, whereas a focus on data management in these architectures is needed to attain value.

In order to answer this question, the methodology for *design science research* (Johannesson & Perjons, 2014) is used to design and evaluate an IoT architecture in a case study. In the case study, a concrete IoT use case, optimizing workspaces in offices, is designed based on a widely supported reference architecture to provide common guidelines and to structure the design process. Further, the integration of capabilities for data management plays a big part in the architecture design.

This paper presents how data management can be integrated in this IoT reference architecture, which is valuable for future architecture designs. This is done by first providing a more comprehensive theoretical background in which several design choices for data management are discussed in section 2. In section 3 the research approach is described. In section 4 findings from the case study are described. Limitations and directions for future research are provided in section 5, and in section 6 a conclusion for this study is provided.

## II. Theoretical Background

The Internet of Things (IoT) has become increasingly popular in recent years. In the IoT vision, *"electronics will be embedded into everyday physical objects, making them 'smart' and letting them seamlessly integrate within the global resulting cyber-physical infrastructure"* (Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012:1497). However, nowadays the term is more used as an umbrella term for more than just smart physical objects – it is also used to describe services and applications that are connected through the internet. These 'things' are able to communicate with other resources that are available over the internet, resulting in added value for the end-user (Cavalcante et al., 2015).

### 1. Relevant IoT challenges

Despite significant academic interest in IoT, there are still challenges for mainstream adoption of IoT (Gubbi et al., 2013; Noronha et al., 2014). The following two which are relevant for this paper are discussed: interoperability and data management

#### 1.1. Non-interoperability of IoT solutions

The first challenge that is discussed is that IoT solutions are mostly non-interoperable, which reduces potential for fully connected systems (Cavalcante et al., 2015; Gubbi et al., 2013; Karzel et al., 2016). Research shows that, due to the increase in popularity of IoT, numerous small and medium-sized enterprises are putting their focus on IoT development (Lilis et al., 2017). As both new and existing businesses expect huge potential from developing IoT devices or services, firms are quick to enforce their new standards. However, as these firms are mostly focused on the development of products and services with a narrow scope (Bassi et al., 2013), efforts towards standardization are increasingly fragmented. Lilis et al. (2017) give smart buildings as an example: as established industrial firms were developing their own standards, the novelty of the market allowed smaller firms and startups to offer their own solutions as well, with the result that *"as more and more parties entered with their own, proprietary implementations, it started to become a Babel tower where hardly any integration between manufacturers' systems was possible"* (Lilis et al., 2017:474).

This fragmentation of standards, and resulting lack of interoperability has given rise to development of reference architectures which define guidelines and building blocks that can be used for the construction of concrete IoT architectures (Cavalcante et al., 2015; Karzel et al., 2016; Muller, 2012). Using these reference architectures in the system design ensures a common foundation, which is needed to achieve interoperability between systems (Muller, 2012; Weyrich & Ebert, 2016).

#### 1.2. Data Management in IoT systems

The second challenge that is discussed is the integration of capabilities regarding data in IoT Architectures. Researchers describe that a clear approach and models for utilizing the (potentially) enormous amounts of data that are collected is currently lacking (Cavalcante et al., 2015; Noronha et al., 2014). At this moment, organizations' focus is more on connecting the most devices, whereas most value is gained when they focus on their capabilities for data management: data integration, storage, processing, and analytics (Noronha et al., 2014; Zdravkovi et al., 2016).

From various *data lifecycle management* descriptions, the following becomes clear: (1) the terms for data management are often used interchangeably, (2) the sequences of these capabilities is varying/other capabilities are mentioned as well, and (3) *integration & storage*, as well as *processing & analytics* are tightly related to each other, or even taking place simultaneously (Abu-Elkheir et al., 2013; TATA, 2017; U.S. Geological Survey, 2015).

For the scope of this thesis, the four capabilities that are mentioned are assessed as they are mentioned most often, and cover mostly the full data lifecycles. First, a formal definition is provided, see Table 1, after which they are discussed.

**Integration**: *"the process of combing data residing at different sources, and providing the user with a unified view of these data"* (Lenzerini, 2002:233).
**Storage**: *"actions and procedures to keep data for some period of time and/or to set data aside for future use, and includes data archiving and/or data submission to a data repository"* (U.S. Geological Survey, 2015).

**Processing**: *"any set of structured activities resulting in the alteration or integration of data"* (U.S. Geological Survey, 2015).
**Analytics**: *"actions and methods performed on data that help describe facts, detect patterns, develop explanations, and test hypotheses"* (U.S. Geological Survey, 2015).

*Table 1 – Definitions of capabilities for data management*

### 1.2.1. *Data integration & storage*

Data integration and storage are discussed first as they are often at the beginning of data lifecycles (Abu-Elkheir et al., 2013; TATA, 2017). In IoT systems, both integration and storage becomes challenging, mainly due to the variety of devices as well as the huge volume of data they collect. When the volume of collected data is huge or growing rapidly, often not all data can be integrated and stored for future use (Jiang et al., 2014), so decisions regarding this need to be taken in the design phase already (e.g. what data to store and what not) (Abu-Elkheir et al., 2013).

Traditionally, data integration took place by moving the data to a centralized location, such as a *data warehouse*, and subsequently merging the data sources (Lans, 2014). A data warehouse is defined as an *"integrated, time-varying, non-volatile collection of data that is used primarily in organizational decision making"* (Chaudhuri & Dayal, 1997:1). Data sources are often merged by performing integration steps on the data, e.g. aggregating values. This is called *schema-on-write* (Brennan & Bakken, 2015). As a result of this, data warehouses contain mostly structured data. As not all data is useful for everyone, subsets of the data are stored in 'subject-oriented' data marts for a specific use (Chaudhuri & Dayal, 1997).

In the IoT-era, it might be difficult to define a schema from the start as IoT systems are increasingly dynamic, e.g. due to changing organizational requirements. Data warehouses are less dynamic; data that does not fit the schema is often not stored (Furlow, 2001; Haller, 2010). Therefore, *data lakes* are becoming increasingly popular as an alternative for data warehouses. In a data lake, mostly raw, unstructured data is stored. A schema is only applied when a user desires to make use of the data: *schema-on-read*. This leads to an *"ever-evolving data model that grows and is modified as new data are encountered and obtained, rather than rejecting data because they do not meet an existing schema"* (Brennan & Bakken, 2015:479)

In both data warehouses and data lakes, data is stored and integrated in one place, *centralized*, which makes it easier to maintain. Yet, as all data needs to be transported through the network to one place, issues regarding performance, scalability and accessibility can occur (Lockner, 2015). If this is the situation, *data decentralization* can be more useful, which means that data is integrated and stored at the place in which it is created, e.g. each office of a large organization has its own data ecosystem independent from the main office. This leads to performance gains as insights can be derived and act upon more quickly. Disadvantages of data centralization are a lack of standardization, a lack of common enforcement of data governance policies, and redundant data infrastructures (Lockner, 2015).

### 1.2.2. *Data processing & Analytics*

After data has been integrated and stored, the next step is to process and analyze the data to gain valuable insights. *"Without this crucial step, data remains just 'data'"* (Noronha et al., 2014:9). An increasing body of literature describes how data analytics can be performed on the ever-growing collection of IoT data, mainly by the availability of a wide range of machine learning algorithms (Strohbach et al., 2015).

In general, data processing and analytics can also be performed either *centralized* or *decentralized*. (Abu-Elkheir et al., 2013; Kulkarni et al., 2016). For the former, processing steps (e.g. data preparation) are performed in a central location, such as a data warehouse. As discussed, this has the disadvantage that all data needs to be transported over the network, which can be troublesome in IoT systems as the amount of data is potentially enormous (Gregorio, 2015). Consequently, decentralized processing has gained traction in recent years. Here, processing steps are moved towards the devices, reducing the volume of data that needs to be transported (Abu-Elkheir et al., 2013). Especially for IoT systems large added values are promised by decentralizing processing capabilities towards the 'edges of the Internet' as data is often collected continuously and value can be gained from real-time decisions (Gregorio, 2015; Noronha et al., 2014).

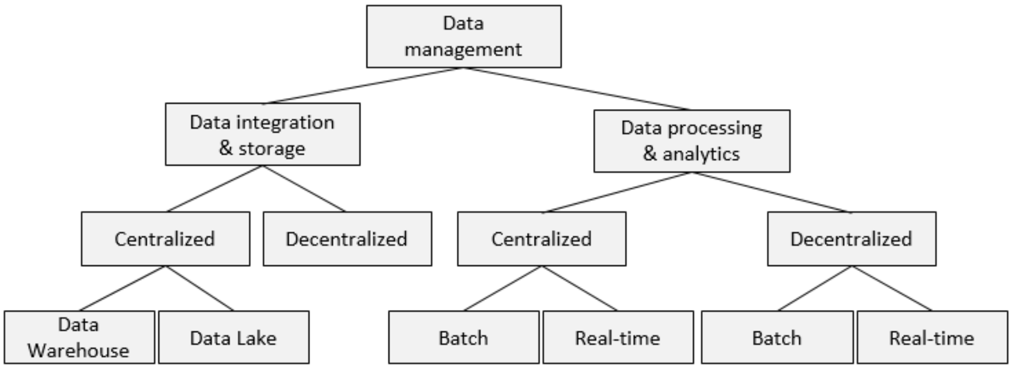


*Figure 1 – Overview of design choices for data management capabilities in IoT systems (non-exhaustive*

Tightly related to centralized and decentralized data processing is the design choice to perform these steps in batches, or in real-time. (Strohbach et al., 2015). Processing and analyzing data in batches means through a schedule or on request, which is often used when the response time is less important (Gartner, 2017; Strohbach et al., 2015). In real-time processing and analytics these steps are performed instantly as the data is collected, which is often used when fast analysis is needed (Strohbach et al., 2015)

These capabilities for data management are thus important design choices that need to be taken in the design-phase of IoT systems. They can be summarized as follows, see Figure 1. An important note is that these choices are non-exhaustive, there are various other options (e.g. hybrid solutions), but the ones presented are mentioned most in literature.

## 2. IoT Reference Architectures

Recent research suggests that most reference architectures that have been designed to cope with the interoperability-challenge of IoT, are either lacking a focus on capabilities for data management, or have only partially fulfilled this integration (Cavalcante et al., 2015).

Cavalcante et al. (2015) have conducted 'an Analysis of Reference Architectures for the Internet of Things' in which two IoT reference architectures are analyzed: IoT-A and WSO2. Findings of their analysis regarding the integration of data management in these architectures are briefly stated. Further, another IoT reference architecture is discussed in this paper: RAMI 4.0. These three reference architectures are discussed as they are varying in focus or development-approach; WSO2 is developed based on practical experience with IoT projects, IoT-A is developed from a more academic perspective, and RAMI4.0 is developed for a specific sector (Bassi et al., 2013; Cavalcante et al., 2015; Fremantle, 2015; VID/VDE, 2015). Therefore, they are expected to provide a good view of the current state-of-art of IoT reference architectures.

### 2.1. IoT Architectural Reference Model

The IoT ARM, IoT-A in short, is developed in the 'Internet of Things Architecture European Project' in close collaboration of academia and businesses. The reference architecture is developed with the goal to be a baseline for IoT system architectures (Bauer et al., 2012).

IoT-A's main deliverables are the reference architecture and guidelines for using this architecture. The reference architecture consists of several views that provide a full overview of the working of IoT systems: The Functional view, Information View, and Deployment and Operation View. The Functional View can be considered as the main view, as it represents all the (high-level) functionalities of the system. These functionalities are presented in Functional Groups (FGs) and Functional Components (FCs). In this Functional View there are no designated FGs for data management, and no FCs that are related to the specific capabilities (e.g. integration or analytics), even though there are designated FGs and FCs for e.g. privacy and security. Cavalcante et al. (2015) state therefore that the management of data is unfulfilled in IoT-A.

### 2.2. WSO2

The WS2O2 reference architecture is developed based on practical experience with the design and implementation of IoT systems (Fremantle, 2015). As a result of this, their architecture is less high-level and less extensive than IoT-A. Even though the WSO2 reference architecture does provide a layer for 'event processing and analytics', Cavalcante et al. (2015) argue that the architecture is too general, as there are no specific views determined, and no functional components identified. Further, there are no guidelines that can be used in the architecting process, therefore, data management is only partially integrated (Cavalcante et al., 2015).

### 2.3. RAMI 4.0

The 'Reference Architecture Model for Industry 4.0' is specifically designed for the requirements of industries, for e.g. smart factories, and is nowadays supported by most major companies in this sector (Weyrich & Ebert, 2016).

The architecture consists of three axes: 'layers', 'life cycle & value stream', and 'hierarchy levels'. Regarding data management, the *Information* layer describes how information from other layers is handled in the system. In this layer, formal descriptions of rules for events are housed for e.g. ensuring data integrity and consistent integration of data.

However, additional capabilities for data management that are discussed in section 2, such as storage and analytics, are not mentioned. This has the consequence that these capabilities are not covered well-enough during the system design. Therefore, data management in is also only partially fulfilled.

## III. Research Approach

In section 2 a lack of capabilities for data management is found in IoT reference architectures. Adopting the design science research methodology by Johannesson & Perjons (2014), the research approach that is used for this paper can be described as follows.

Through a case study, an IoT architecture is designed for a specific use case: optimizing workspaces in offices. First, a suitable reference architecture is selected to provide guidance in the design process. During the architecture design, design choices regarding capabilities for data management in the use case are identified and integrated in the architecture. At last, the way data management is integrated in the architecture is generalized and proposed as an extension for the reference architecture. The research approach is described by first providing a short description of the use case, and subsequently describing the architecture design process.

The specific use case that will be used for the design of the IoT architecture is *workspace optimization*. This use case is selected for two reasons: Firstly, for this study, access is provided to smart building The Edge in Amsterdam. This building is certified as 'the world's greenest' and consists of more than 20.000 sensors that collect a variety of data (Wakefield, 2016). Due to its unique features, the building has been featured in various media outings, such as the BBC (Wakefield, 2016), Bloomberg (Randall, 2015), and the Financial Times (Cox, 2017). Facility management and employees in the building are struggling with a highly dynamic office occupation, therefore a solution for optimizing workspaces is desired. Secondly, there is already data being collected in The Edge, thus best practices on data management in the building can be used in the architecture design.

**Use case: workspace optimization**

In recent years, office occupation has become increasingly dynamic, as technological developments allow employees to work from e.g. home or the client's office (Faraj & Azad, 2012; Spinuzzi, 2007). The layout of offices are changing as a result of this, hot-desking (no assigned desks) and open floor plans are nowadays increasingly used to cope with these dynamics (Hirst, 2011; Millward et al., 2007). However, disadvantages of this trend are e.g. difficulties with finding vacant desks on busy days, and finding colleagues in the building (Biggart et al., 2016; Slawson, 2016; UVA, 2014). Workspace optimization is therefore gaining traction in both business and academia. In journals and whitepapers, the following benefits are mentioned: (1) it provides insights in building usage. (2) By collecting data to the desk level, employees can locate vacant desks. (3) Employees can find their colleagues' location (Serraview, 2015). (4) Energy consumption can be optimized, e.g. by closing unused floors (Nguyen & Aiello, 2013; Paola et al., 2014). (5) Emergency situations and security can be handled better by getting insight in the number and precise location of employees (Hitiyise et al., 2016; Nyarko & Wright-Brown, 2013).

The collection of data that is needed for this takes place through several sensors in buildings that can be connected to gain additional value, e.g. providing employees with suggestions for desks based on vacancy and the location of their colleagues. At this moment, there is no structured design/architecture that can be used to implement such a solution. Even though studies are available that discuss techniques for occupancy measuring in buildings based on sensors (Balaji et al., 2013; Melfi et al., 2011), they are mainly based on small-scale test settings and conceptual ideas.

For this use case, the IoT-A reference architecture is most suitable to provide common guidelines, as this is the only IoT reference architecture of which development has mostly been finished, which is preferred as this means that more documentation is available, and that no major changes are expected (Weyrich & Ebert, 2016). Further, IoT-A is widely supported by both businesses and academia, and is already successfully applied in several projects (COSMOS, 2017; FIESTA, 2017).

**Design Process**

In the design process that IoT-A prescribes the following is needed for the design: (1) relevant stakeholders, (2) list of applicable unified requirements, and (3) additional requirements (Carrez et al., 2013).

First, a small focus group is organized to discuss and agree upon the specificities of the workspace optimization use case. After that, two research methods are used to design the architecture; a desk study and interviews. The desk study is used to collect requirements from best practices by assessing (1) IoT-A project deliverables, (2) deliverables of projects that have applied IoT-A (such as COSMOS (2017) and FIESTA (2017)), and (3) literature on techniques for workspace optimization. These project documents are also used to get an indication of the relevant stakeholders that need to be included.

Following that, two rounds of interviews are conducted. In the first round, relevant stakeholders are interviewed to collect additional requirements for the architecture. In the second-round experts are consulted to evaluate the architecture and the design choices.

## IV. Research Findings

After performing the research as described in section 3, the following findings are obtained.

### 1. Focus group findings

In the focus group session, the specificities of the use case are discussed with several employees in The Edge, real estate consultants, and (IoT) architecture consultants. In this session, the use case is defined as follows:

*Employees use a smartphone application to access the solution that provides them with suggestions for workspaces. Further, employees are able to get an overview of vacant desks/meeting rooms, and find the location of their colleague in the building.*

The description of the use case will subsequently be used in the remainder of the design process.

### 2. Desk study findings

In the desk study, project documents of IoT-A are consulted to retrieve an initial set of requirements for the IoT system, and to get an indication of relevant stakeholders to involve.

IoT-A provides a list of unified requirements (UNIs) that consist of generalized requirements which are extrapolated from projects that have already applied the IoT-A reference architecture. In total, 184 UNIs are identified by IoT-A, of which 30 were rated to be applicable for the workspace optimization solution, based on the use case description. As IoT-A describes the UNIs in general terms, the descriptions are slightly adapted to fit the workspace optimization solution.

Next to that, project documents and the focus group indicate the stakeholders in the first column of Table 2 are important to involve in the process.

| Stakeholder | Involve |
|---|---|
| Building owner | |
| Building tenant | |
| Information systems manager | ✓ |
| Data scientist | ✓ |
| Privacy officer | ✓ |
| Employee | ✓ |
| Visitor | |
| Facility manager | ✓ |
| Contractor | |

*Table 21 – Findings stakeholder identification and analysis*

After conducting a stakeholder analysis as prescribed by Enserink et al. (2010), the second column of Table 2 indicates whether the stakeholders are found to be important enough to be involved in the remainder of the design process, based on their power and interest in the system.

At last, literature on techniques for workspace optimization is analyzed to get a better understanding of needs for such a solution. Based on this, types of sensors that are needed, as well as techniques for occupancy measurement are selected. Examples of this are desk sensors to derive desk vacancy (OccupEye, 2017), and WiFi triangulation to retrieve employee's location with high accuracy (Akkaya et al., 2015; Balaji et al., 2013).

### 3. Interview findings

The interviews are conducted in two rounds. In the first round, *requirement elicitation*, important stakeholders are interviewed to collect additional requirements for the system. In total 16 interviews are conducted. The interviews are analyzed by performing the analytical procedure *template analysis*, in which the interview transcriptions are coded, and codes are subsequently used to find requirements for the system, as well as the support for these requirements among respondents (e.g. the frequency of a certain code can indicate the support for a requirement among respondents) (King, 2012).

Regarding data management, the following findings are obtained in the interviews. Quotes that are provided are literal statements from the interviews.

*Round 1: requirement elicitation*

It is argued that a real-time overview of currently occupied workspace is needed to provide useful, high accuracy suggestions. Also, historical data needs to be stored in order to useful 'clusters': *"Ideally, you have a real-time overview of current occupation, but also historical data to e.g. create zones" (data scientist)*. Further, data quality needs to be high and some manual work might be needed on beforehand, e.g. to facilitate preferences for workspaces, a preference to work in a quiet area is only possible if these areas are labeled first, otherwise accuracy will be low: *"the algorithms might have a hard time" (Information systems manager)*. Further, in order to ensure that the system has a high performance, there should be relatively powerful server on which the model runs. However, there can be an efficiency gain by not 'running the model' ad-hoc, the clusters of an employee's preferred areas and preferred colleagues can be created e.g. once per week or month. *"When the employee asks for a suggestion, a simple 'read'-action is performed, which is much more efficient than running the model each time" (data scientist).*

Further, employees' preference for tracking their location is to base this on the location of their laptop: *"The laptop needs to be used, because your laptop is at the place where you work" (employee)*. Further, privacy is seen as an important constraint in this solution. Several employees have stated that they consider it very important that their personal data (e.g. their location) is handled carefully, and that they exactly know what this data is used for. The privacy officer even states that an opt-in is legally required, so certain measures need to be in place that prevent linking laptops with their owner if they did not provide access.

At last, the wish to connect other data sources to the system was identified. In particular software applications that are currently being used by the employees (e.g. IM and a Calendar) are argued to have valuable data that can be used to improve suggestions: *"A connection with your agenda to ensure that your workspace is nearby your meetings would be nice" (employee).*

In total, 16 requirements are collected from the interviews. Combined with the 30 UNIs, this makes 46 requirements, of which 26 are rated as high priority. These requirements are used to design an initial version of the IoT architecture that integrates capabilities for data management integrated. See Appendix A for an overview of the requirements with which this architecture is designed to comply.

*Round 2: architecture evaluation*

In the second round of interviews, the architecture design is evaluated through interviews with experts: two IoT architects, one IT experts and one data scientist.

Main findings from these interviews regarding data management are the following: firstly, the experts agree that the focus on capabilities for data management is very important in IoT systems: *"IoT is so data-driven, I am convinced that it deserves a place in this architecture, so I am sure it is a good addition" (IoT architect)*. They are aware of the importance of it due to their practical experience: *"If you collect data from all kinds of sensors, you need to have a structured way of working to handle that. You need to have clear agreements regarding e.g. the data model and quality of source data" (IoT expert)*. Next to that, a centralized solution for integration & storage is argued to be good enough for this solution, as the use case is focused on one office, data does need to be transported over long distances.

Further, a data lake with data marts is argued to be a good design choice for this system, as it allows for the creation of future use cases by storing all data: *"If you use a data warehouse, you have to specify the type of data exactly on beforehand. It is easier to use a data*

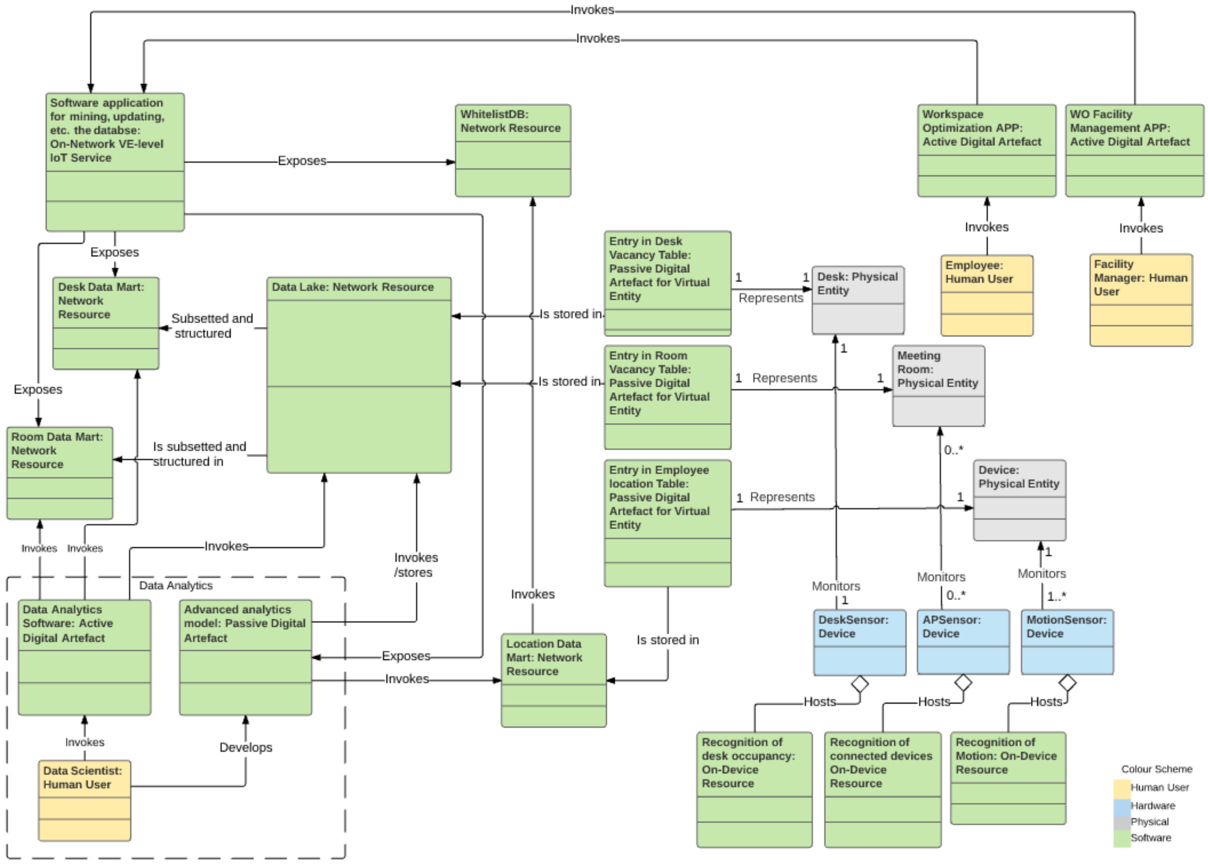


*Figure 2 – Workspace optimization Information View*

*lake, then you can store all the data" (data scientist).* However, as privacy is also an important aspect, wise decisions need to be taken regarding the kind of data that is allowed to be stored: *"privacy is so important, you have to comply with law; you cannot store everything" (data scientist).*

At last, it is stated that real-time data is almost always preferred for IoT solutions, but sometimes batch processing & analytics might be required to handle constraints regarding the devices that are used, or constraints regarding privacy.

## 4. Design choices data management

Based on the findings from the desk study and interviews, two architectural views have been created for the workspace optimization IoT solution. The Information View, which shows the information flow is presented in Figure 2. The Functional View that contains the functions of the system is presented in Figure 3. Further a process View has been designed to clarify how the system is used by employees, see Appendix B. The design choices for the architectural views are described below.

*Data integration & storage*

A centralized solution for data integration & storage is chosen to be best, as this is improves data quality (no replication needed as data is stored in one place). A data lake with data marts is then used to store all data in a raw, unstructured format. Data for specific uses, e.g. for providing an overview of vacant desks, are integrated and stored in data marts. A data lake allows e.g. data scientists to experiment with new use cases and retrieve additional insights over time, as all data is stored. To cope with the privacy challenge, a separate database will be used to store links between employees' unique identifier and their devices if they opt-in for the system.

*Data processing & analytics*

For data processing & analytics a centralized solution is chosen as well. This means that processing (e.g. prepare data for analytics) and (advanced) analytics are performed on all data, instead of at the device-level. Again, this is chosen because all data remains in the office, the distance to transport data is not large. Further, this will happen both in batches as in real-time. Batch processing & analytics are used for the creation of 'clusters' that are used for the suggestion of

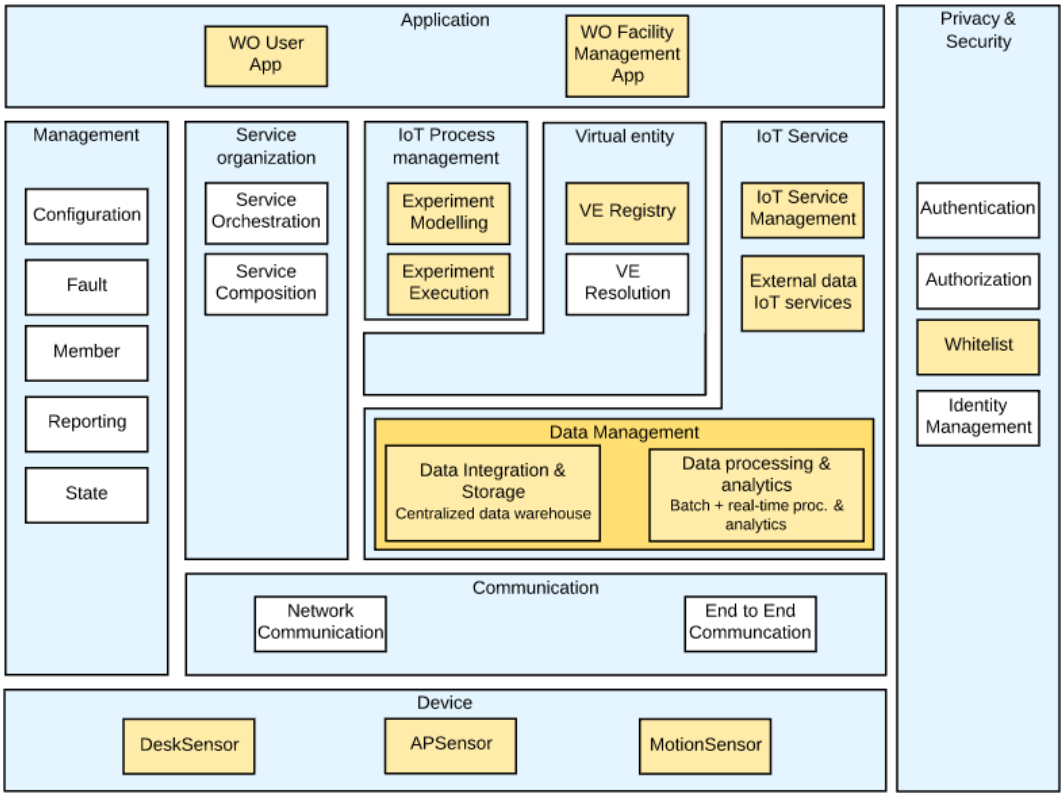


*Figure 3 – Workspace optimization Functional View. Blue and white 'boxes' represent Functional Groups (FGs) and Functional Components (FCs) respectively (IoT-A default). Yellow 'boxes' represent FGs and FCs that are added/adapted for the Workspace Optimization solution*

workspaces. As it is expected that these clusters don't change very often, they don't need to be computed in real-time. However, the actual vacancy-status of desks/meeting rooms, and the location of employees needs to be available in real-time.

**5. Integration of data management in IoT-A**

In Figure 4 an extension of IoT-A's Functional View is proposed. In this extension, a *Data Management FG* is added as a sub-FG inside *IoT Service FG*, as well as a FC for external data IoT Services. This extension has two advantages. Firstly, by integrating the FG as a sub-FG, existing interrelationships between FG's remain the same as they are in IoT-A's original Functional View (Appendix A1). Secondly, the explicit notion of data management forces systems designers (that use IoT-A) to take design choices regarding this during the first phases of design already, in section 2 is discussed that this is needed to attain value from IoT systems.

## V. Limitations and Future Research

Even though the research has been conducted carefully, this study has some limitations. The three most important limitations are discussed here. First of all, four capabilities for data management are discussed and integrated in the proposed extension of IoT-A. However, in section 2 is already stated that numerous capabilities exists, and that almost all *data lifecycle descriptions* are varying. Even though these four capabilities are mentioned most often in these descriptions, and seem to cover the data lifecycles from beginning to end, not all capabilities for data management are covered in this study (e.g. share).

Secondly, a more sophisticated framework might be needed to make design choices on the type of capability for data management that is needed in a certain system. In this study, several choices are provided (e.g. centralized – data warehouse, or centralized – data lake), but in reality various other design choices can be made.

At last, the architecture for workspace optimization has not been demonstrated – no solution architecture has been developed. This was out-of-scope for this study due to time constraints. A solution architecture might have resulted in a better evaluation-process, as a complete demonstration of the system could have been provided to the experts.

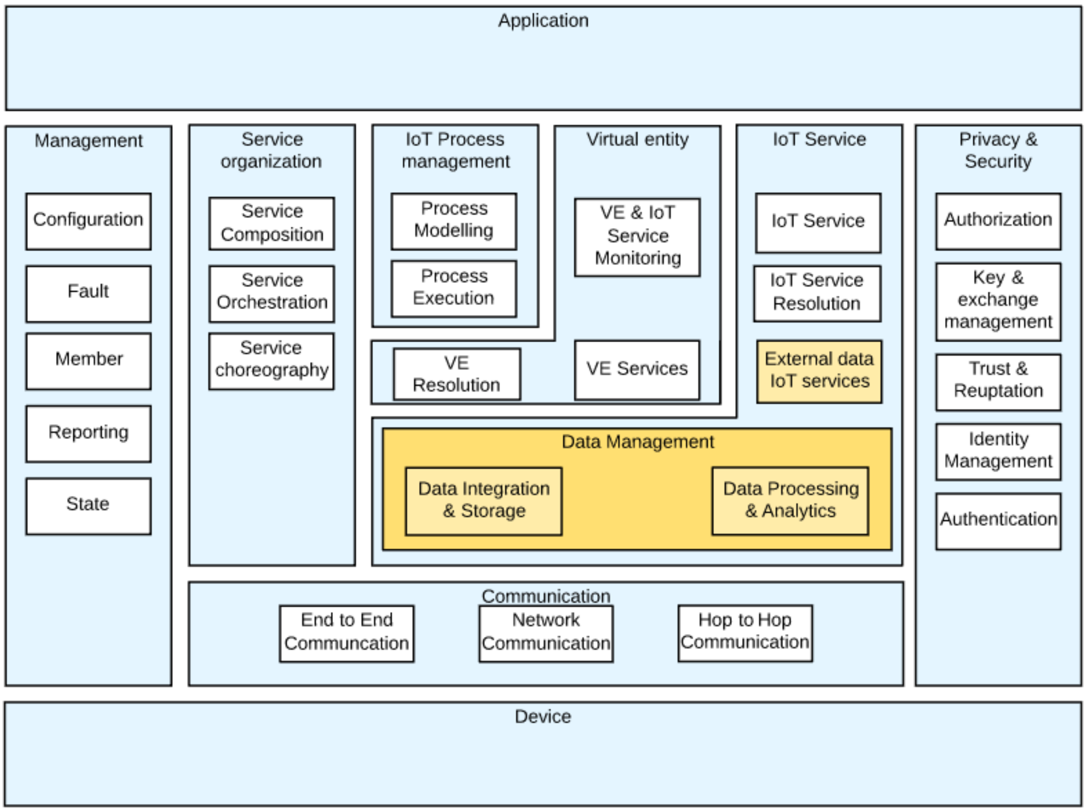


*Figure 4 – Proposed extension to IoT-A's Functional*

Next to the limitations, this study also provides three directions for future research. The first one is closely related to the aforementioned limitation about the need for a more comprehensive framework for data management design choices. This framework can be used by systems designers to select suitable data management design choices, based on characteristics of their envisioned system. The design choices can subsequently be integrated in their IoT architecture to ensure a focus on this during the system design.

The second direction for future research is that the case study can be extended by demonstrating the architecture in a smart building. A *solution architecture* (which is used for the implementation of the system) can be designed using the architectural views (Figure 2 and Figure 3) as guidelines, see Appendix C for a process view of this implementation process.

The third direction for future research is to integrate capabilities for data management in other IoT reference architectures. For this study, IoT-A is used, but in section 2, two other reference architectures are discussed that lack this integration: WSO2 and RAMI4.0. Future research can conduct similar studies to improve those reference architectures as well.

## VI. Conclusion

After conducting the study, the following concluding statements can be made

- It is found that that IoT reference architectures that are developed with the objective to, among others, improve interoperability between IoT solutions are lacking a focus on capabilities for data management.
- An extension to the IoT-A Functional View is proposed that that includes capabilities for data management. This extension (Figure 4) can be by future users of the IoT-A reference architecture to include in their system design. Further, an overview of (non-exhaustive) design choices regarding data management is provided, this can be used to select suitable design choices.
- It is found that current researchers in the field of workspace optimization are mainly focused on techniques to e.g. measure building occupancy. An architecture to structure the design and implementation of such a solution was found to be lacking. In this study, research in this field is stimulated by providing two architectural views; one for an overview of information flows in the system (Figure 2), and one for an overview of important functionalities (Figure 3). Further, an

implementation process view is designed to indicate how these views can be used for the design of a *solution architecture* (appendix C).

Thus, this study is valuable for IoT development, as it describes how the two challenges for IoT that are defined at the start of this paper; *non-interoperability* of solutions and a lack of capabilities for *data management* in the design phase of IoT systems can be tackled. By using the extension of the reference architecture that this study proposes, both interoperability, as well as a focus on data management during the design phase is ensured.

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# Appendices

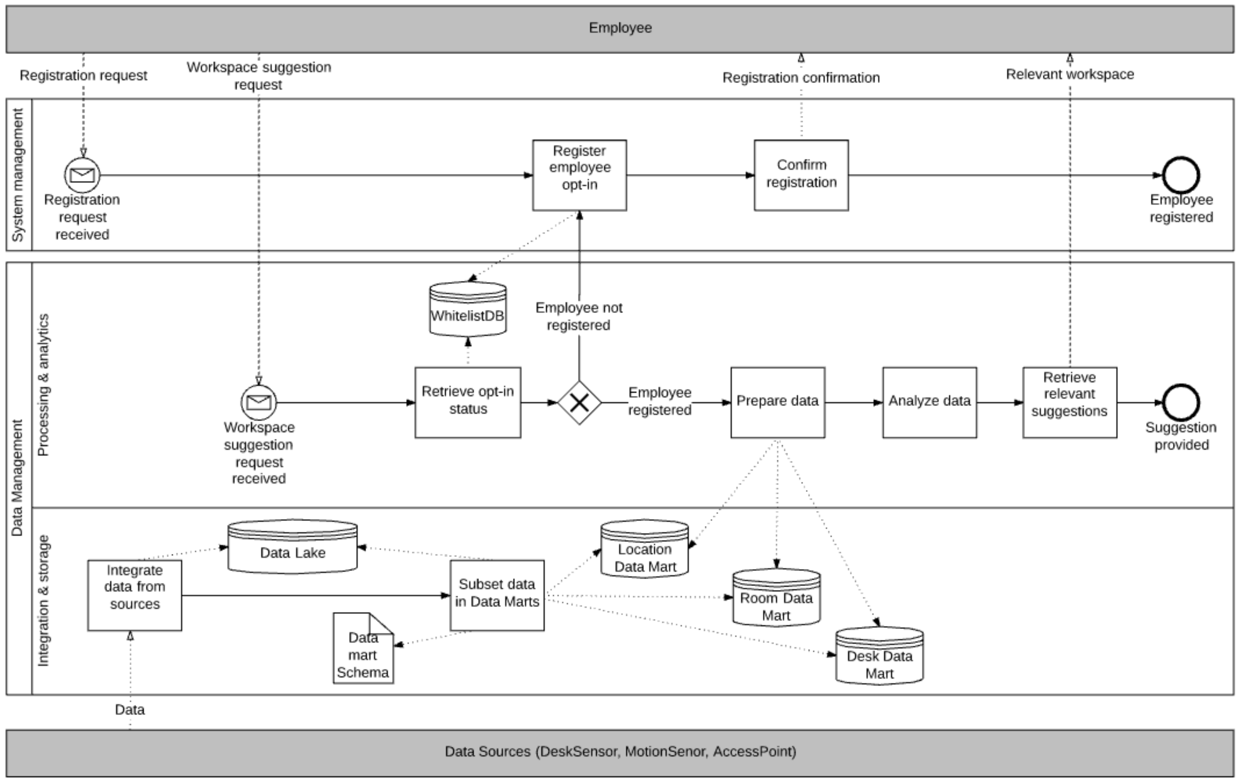
## Appendix A: Requirements for a Workspace Optimization IoT solution

| UNI ID | Description | Requirement Type |
|---|---|---|
| UNI.001 | Users are able to use the service anonymously | Non-functional |
| UNI.002 | Users have control how their data is exposed to other users | Non-functional |
| UNI.005 | The system supports event-based, periodic and/or autonomous communication | Functional |
| UNI.016 | The system supports physical entity location tracking (logical location) | Functional |
| UNI.018 | The system supports capabilities for data management (integration & storage, processing & analytics) | Functional |
| UNI.050 | The system supports mobile physical entities | Non-functional |
| UNI.062 | The system provides trusted and secure communication and information management | Design constraints |
| UNI.067 | The system provides different access permissions to information | Functional |
| UNI.410 | The system restricts who can update and delete Digital Entity history | Functional |
| UNI.414 | The system enables the dynamic discovery of virtual entities and their services | Functional |
| UNI.423 | When performing discovery, resolution or lookup, the system must respect any aspect of privacy, including the possibility to retrieve information about or related to people. In addition some services should be accessible in an anonymous way, while others might require an explicit authentication or authorization of the user. | Functional |
| UNI.502 | The system prevents a device from being activated without the consent of the owner. | Non-functional |
| UNI.503 | The system makes it be possible to change the owner of a device | Functional |
| UNI.504 | The system prevents tracking of the identifier of the device by unauthorized entities. | Non-functional |
| UNI.506 | The system supports communication across devices by aid of standardized communication interfaces. | Design Constraint |
| UNI.606 | The system makes the traceability of digital activities impossible | Non-functional |

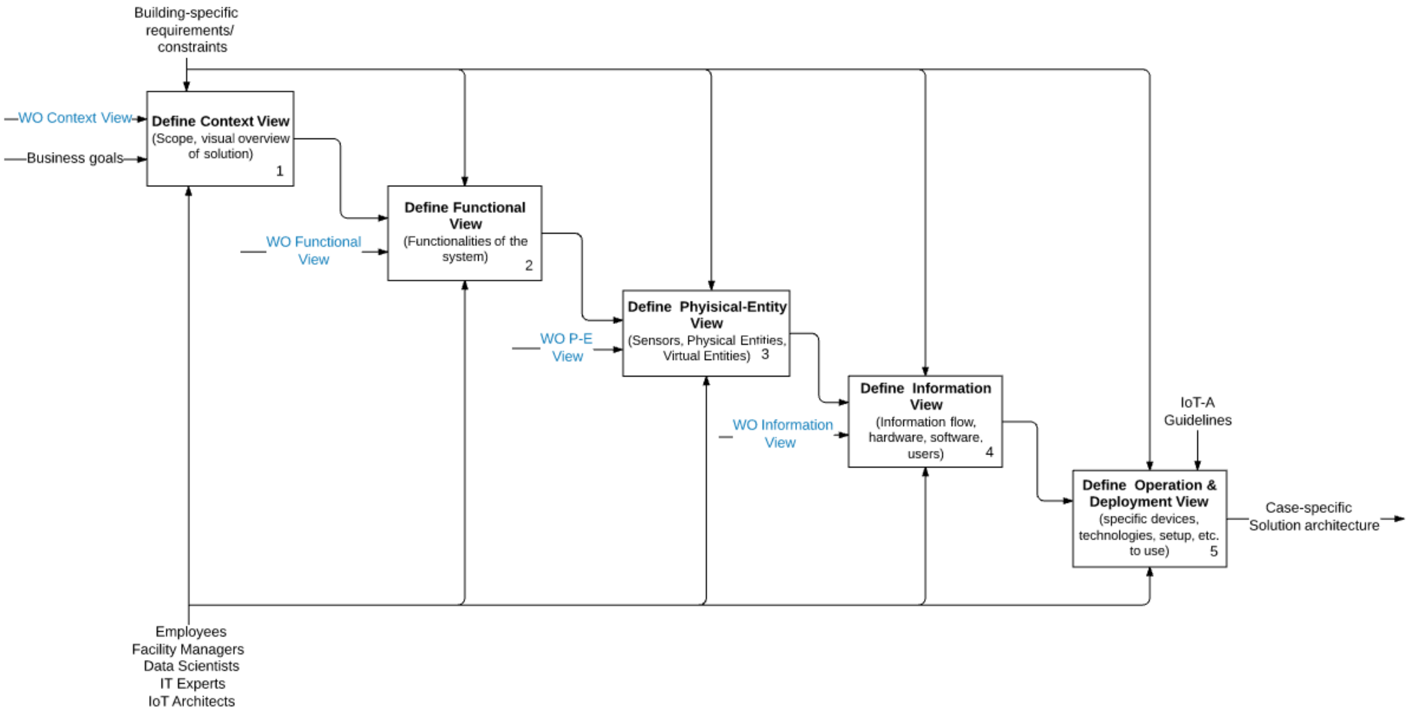
| Req.ID | Description | Requirement type |
|---|---|---|
| 1. | The system enables employees to disable tracking (opt-out) | Functional |
| 2. | The system needs employees' approval to start tracking them (opt-in) | Functional |
| 4. | The system is able to find IoT devices automatically | Non-functional |
| 5. | The system determines the employee's location based on the location of their laptop | Functional |
| 8. | The system collects and stores user identifiable data | Non-functional |
| 9. | The system needs to have a high accuracy of suggestions | Non-functional |
| 10. | The system needs to be able to work in real-time | Non-functional |
| 11. | The systems needs to be easy to use and easy to understand | Non-functional |
| 12. | The system allows employees to provide their preference for a workspace | Functional |
| 16. | The system supports various user permissions for the system | Functional |

The first part of the requirements (UNIs) are adapted from IoT-A's *Unified Requirements*. The second part of the requirements are collected through interviews with relevant stakeholders. Only High priority requirements are presented in this table.

## Appendix B: System Usage Process View




## Appendix C: Implementation Process View



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