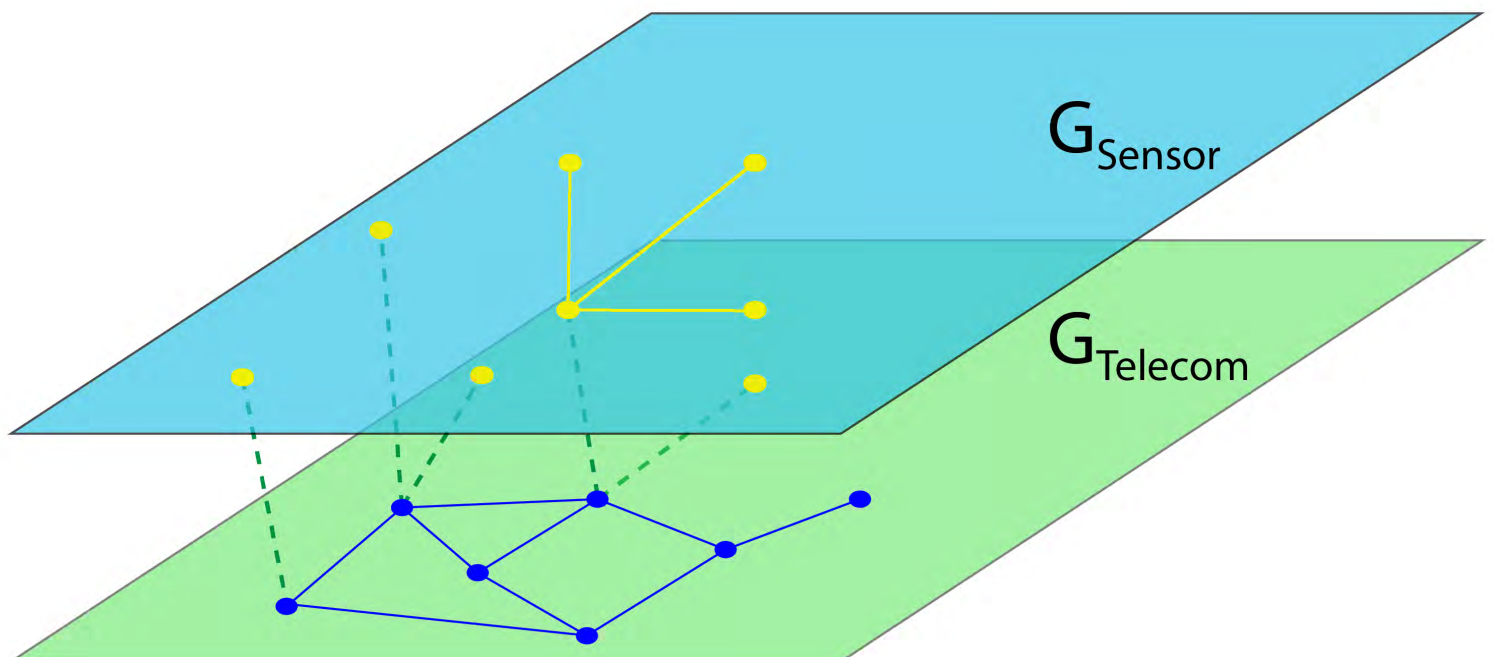# Interdependent sensor and telecommunication networks

Practical connectivity options for optimising sensor networks in the urban public space

Erik Lemmens

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Interdependent sensor and telecommunication networks

Practical connectivity options for optimising sensor networks in the urban public space

by

Erik Lemmens

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TUDelft

Abstract

For several years, the concept of the *Internet of Things* is gaining attention. Starting with the academic community, it has since been picked up by the industry due to its potential value. The term Internet of Things is frequently used to describe the emergence of sensors in equipment and objects, both in industrial and residential settings, and the ability to connect these sensors to the internet in order to enable new applications. The declining cost of sensor technology has triggered local governments to consider deploying additional sensors in the public space as well, contributing to the trend towards *Smart Cities*. Smart City applications, enabled by the Internet of Things, could help governmental organisations to solve complex problems in modern cities by improving insight in municipal processes. Municipalities are currently challenged with many policy issues and optimisation problems in parallel. A few examples include improving air quality in urban environments while supporting mobility, management and maintenance of objects in the public space and public safety within the city. Likely sensors are able to provide citizens and municipality employees with more accurate and detailed information compared to information derived from manually gathered data, which is for some types of information still current practice.

Smart City concepts and enabling technologies (e.g. Internet of Things) provide an attractive perspective for cities aiming to improve the quality of life of their citizens, reduce their cost level and be more competitive compared to other cities. Because a municipality can have different types of areas, like residential neighbourhoods, commercial areas and industrial zones, the required number of sensors and sensor types differs in correspondence with the specific type of area. Understanding these differences will help municipalities with accurately planning sensor deployment. Deploying sensors in the urban public space could be a means to contribute to the city goals, but in order to avoid sub-optimal investments an analysis of the available technological enablers is essential.

This research project aims to contribute to the optimisation problem sketched above by providing answers to the following three research questions:

RQ 1 Which types of sensors are promising, now and in the future, for a Dutch municipality like The Hague?

RQ 2 What types of telecommunication access technologies are currently available to support the connection of sensors in urban public space?

RQ 3 Given an amount of sensors of different types and requirements, what is the cost-optimal way of connecting them using existing telecommunication access technologies?

Because the research has been carried out in The Netherlands, the largest Dutch telecommunications operator, KPN, has been approached to contribute to the technology perspective of this research. KPN is assumed to be representative for the current commercially available technologies in the urban public space. To obtain insights into the functioning and requirements of local governments, The Hague municipality has been approached to cooperate with this research project.

Chapter 3 elaborates on the first two research questions. One of the main findings consists of an inventory of 8 currently used sensor types within the city of The Hague, being:

1. Air quality sensors

2. Induction loop detectors

3. Ground water level sensors

4. Pneumatic tube detectors

5. Radar detectors

6. Speed cameras

7. Weather stations (often includes air temperature, air humidity and wind speed sensors)

8. Video cameras

By performing a series of interviews within the municipal organisation, a selection of 11 sensor types has been found that seems *promising* for future Smart City applications within the city. These sensor types are:

1. Air quality sensor
2. Air temperature sensor
3. Ground temperature sensor
4. Garbage level sensor
5. Sound level sensor
6. Vehicle speed sensor
7. Vehicle detection sensor
8. Parking space occupation sensor
9. Water level sensor
10. Wifi/Bluetooth sensor
11. Video camera

Together these two sets of sensor types form the answer to research question 1.

In cooperation with municipality experts, a minimum and a maximum scenario has been defined with the expected number of sensors to be deployed in the entire city of The Hague. Part of the list of selected sensor types have already been deployed in a pilot area in the area of Zichtenburg in the city of The Hague. From this pilot, useful information regarding the produced amount of data has been obtained and used to feed the cost-optimisation model developed in chapter 4.

Another main finding consists of the selection of suitable telecommunication access technologies available within the city of The Hague for the connection of sensors to a telecom network. Based on a number of selection criteria, the following technologies have been identified as promising:

- ZigBee; A wireless technology used to form communication networks providing low throughput connections to nodes at short radio ranges. Only used to provide sensor-to-sensor connections or sensor-to-sink connections.

- LoRaWAN; A wireless technology belonging to the class of Low Power Wide Area Networks (LP-WAN), intended to provide low throughput connections at long radio ranges.

- Long Term Evolution (LTE); A wireless network standard for data communication in mobile networks providing high throughput to nodes.

- Digital Subscriber Line (DSL); A standard for wired data communication over copper cabling. More specifically, the variants VDSL2, VVDSL2 and their pair-bonding versions are considered promising for use in the city of The Hague.

- Optical fibre; A physical medium used for providing very high data throughput.

Thereby answering research question 2.

In order to answer the third research question, a layered interdependent network model has been developed to perform a network cost-optimisation. More specifically, the problem can be defined as a link allocation problem between nodes in two separate networks under constraints imposed by the physical world. The two interdependent networks in this case are the sensor network and the telecom network.

The interdependent network model has been implemented in MATLAB in order to perform simulations on actual telecom and public space data. From the simulations it can be observed that the cost-optimal way of connecting sensors to a telecom network will involve multiple telecom access technologies, based on the type of sensor and the location of the sensor. Most of the sensor types relevant for use in the urban public space can be connected with cost-efficient LP-WAN technology. When requirements for measurement frequency demand real time transmissions, an LTE connection seems an appropriate substitution for LP-WANs. This will likely be the case for the sensors that have been classified in table 6.2 as continuously transmitting. The sensor types that have throughput requirements exceeding the capabilities of wireless access types, are in the city of The Hague best served, from a cost-perspective, by a DSL based connectivity option.

Simulation part C has shown that a cost-optimisation based on the location of sensor nodes is able to reduce the total capital expenditure of network infrastructure by 48,8% compared to following the placement rules without optimisation. The operational expenditures can be reduced by replacing links from sensor nodes to telecom nodes with ad-hoc sensor to sensor links supported by ZigBee, as is shown in simulation part D. This is done by clustering nodes that are geographically close together and assigning a sink within each cluster. The sink node is then capable of relaying data for other sensor nodes within d_{max} of the sink node. A d_{max} value of 50 meter resulted in a cost-saving of 9,14%.

Preface

The completion of this thesis marks the final chapter of my studies in Electrical Engineering at Delft University of Technology. The research project that led to this thesis has been performed at KPN in close collaboration with The Hague municipality. Academic supervision has been provided by the Network, Architectures and Services (NAS) group at the faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) of TU Delft. The goal of the project has been to investigate the developments in sensor technology used in the urban public space in The Netherlands and to develop a cost-optimisation model to efficiently connect future sensors to a telecommunication network. All in the context of the current trends towards Smart Cities and the Internet of Things.

Many people have contributed to the outcomes of this research project and the completion of this document. First and foremost, I would like to thank my thesis supervisor Dr. ing. Edgar van Boven for offering the opportunity to start this work and for his support and enthusiasm over the course of the project. I would also like to thank Ilse van der Heijden for allowing me to perform this research project within KPN and all the architects for the stimulating work environment. Furthermore, I am grateful to all consulted experts that have provided input for this project. In particular, I would like to thank Douwe Zijlstra and Sander Kleinstra from The Hague municipality for all the time and effort they have spent.

Last but not least, I have to thank my friends and family for providing all the necessary support during this extensive period of time.

Erik Lemmens
Delft, 2017

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Introduction

For several years, the concept of the *Internet of Things* is gaining attention both from the academic community as well as from the industry [49]. This is supported by consultant reports [15] and the position it occupies on the Gartner Hype Cycle for Emerging Technologies (figure 1.1a shows the 2015 hype curve indicating the Internet of Things with a red dot. Figure 1.1b shows a 2016 version of the dedicated Internet of Things hype curve including constituent parts [33]). Companies active in device manufacturing, communications and software development are trying to come up with new business models in order to profit from this attention because the potential revenues have been estimated to be significant and increasing [47]. Although frequently mentioned in publications, the term Internet of Things [8] together with similar terms as Internet of Everything [23], Internet of Devices [88] and the older term Machine-to-Machine communication (M2M) lack a clear and generally accepted definition and are often used interchangeably. The consequence of this ambiguity is that these terms have become an umbrella to describe a large variety of products and enabling technologies.

(a) Internet of Things on the Gartner hype-curve in 2015

(b) Dedicated Internet of Things hype curve in 2016 including constituent parts
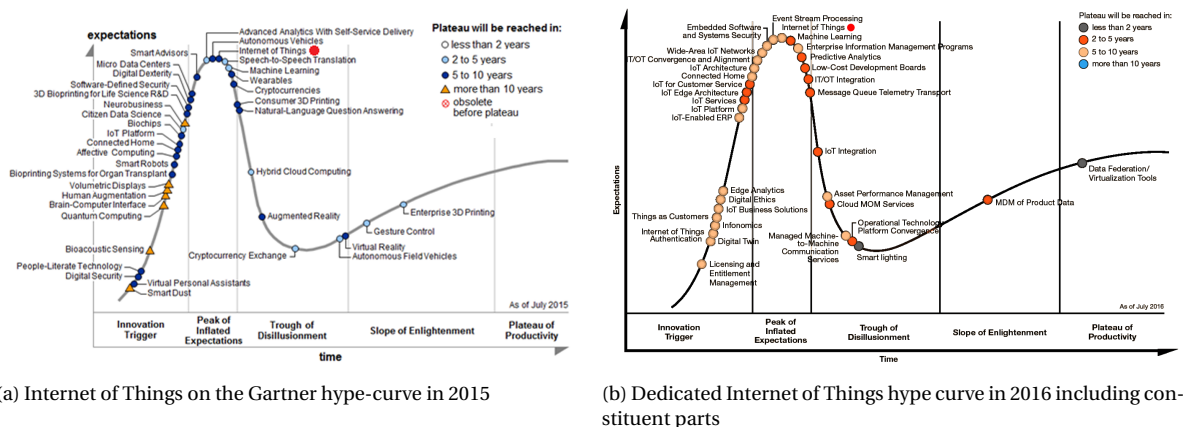
Figure 1.1: Internet of Things on the Gartner hype-curve

The term Internet of Things is frequently used to describe the emergence of sensors in everyday appliances, both in industrial and residential settings, and the ability to connect these sensors to the internet in order to enable new applications. The declining cost of sensor technology has triggered local governments to consider deploying sensors in public space as well. This could help governmental organizations to solve complex problems in modern cities by improving insight in municipal processes [23]. Municipalities are currently challenged with many policy issues and optimization problems in parallel. A few examples include improving air quality in urban environments while supporting mobility, management and maintenance of objects in the public space and public safety within the city. Likely sensors are able to provide citizens and municipality employees with more accurate and detailed information compared to information derived from

manual gathering, which is for some types of information still current practice [89]. The trend of increasing the presence of sensors in the urban public space can already be observed in many cities in the Netherlands and around the world [74] [96] [111], and is often considered to be part of the evolution towards *Smart Cities*. Cities have multiple drivers to increase their smartness [23], like the competition to attract skilled workers and businesses, increasing pressure on local (natural) resources and infrastructures and overcoming the consequences of a changing climate. It is for this reason that the deployment of public space sensors and sensor networks will most likely continue in the future at a larger scale [15].

Research on sensor networks often concentrates on the concept of wireless ad-hoc sensor networks [4]. Wireless ad-hoc networks [43] are characterized by a number of properties that clearly distinguish them from other types of wireless networks. Nodes can autonomously setup dynamic communication links to other nodes in a decentralized way, without a predetermined infrastructure to support this communication. In ad-hoc networks, nodes are equipped with an energy efficient radio transmitter and receiver using a low overhead protocol. This way nodes can communicate with each other to transport their data within the network and possibly further onto the internet via a gateway. Ad-hoc networking has many advantages, such as the absence of investment cost for a predetermined communication infrastructure and the ability to adapt to changes in network topology very rapidly. One of the downsides of using an ad-hoc network structure is that the radio ranges between nodes in the network should be short enough for the nodes to be able to reach each other and provide connectivity for an entire area. In large cities, keeping the radio ranges short can pose a problem because sensor nodes are not going to be deployed spatially uniform across the city due to different sensor requirements per area type. Increasing the number of hops in the network could be a way to keep the radio ranges short, but research has shown that hopcount in ad-hoc networks is limited [43] and compromises total network throughput.

To overcome the downsides of local ad-hoc sensor networks, new types of managed telecom networks are being developed specifically to address the requirements of connecting sensors. Such a network is often called a Low Power Wide Area Network (LPWAN), and is supposed to provide centrally managed cost-optimal, low bandwidth and low power wide area connectivity to devices. One of these new network technologies is LoRaWAN, developed by the LoRa-Alliance [5]. LoRaWAN is currently being rolled out at a nation wide scale in the Netherlands. Other comparable technologies like Narrowband-IoT and LTE-M [7] are currently being developed and standardized by the major telecommunication bodies [39]. Several telecommunications operators (hereafter called operators) have confirmed that they are planning to roll out one of these technologies as their LPWAN solution [107] [95]. However, these new LPWANs are not always capable of meeting the diverse requirements of all sensor types that are available on the market and other options remain necessary to be able to provide a complementary access solution to all types of sensors in the field.

1.1. Problem statement

Smart City concepts and enabling technologies (e.g. Internet of Things) provide an attractive perspective for cities aiming to improve the quality of life of their citizens, reduce their cost level and be more competitive compared to other cities. Deploying sensors in the urban public space could be a means to contribute to the city goals, but in order to avoid suboptimal investments an analysis of the available technological enablers is essential.

Deploying sensors across an entire municipality leads to a number of challenges, not in the least because the area involved can easily span dozens of square kilometres in an urban environment. As illustrated in figure 1.2, information desired in a specific Smart City application can be derived from multiple data sources, one of which are sensors in the urban public space. Because a municipality can have different types of areas, like residential neighbourhoods, commercial areas and industrial zones, the required number of sensors and sensor types could differ in correspondence with the specific type of area. Understanding these differences will help municipalities with accurately planning sensor deployment.

Having determined, for a specific area, the required number and types of sensors it is essential to mount the sensors in a reliable and secure way in the public space. The urban public space is already equiped with var-
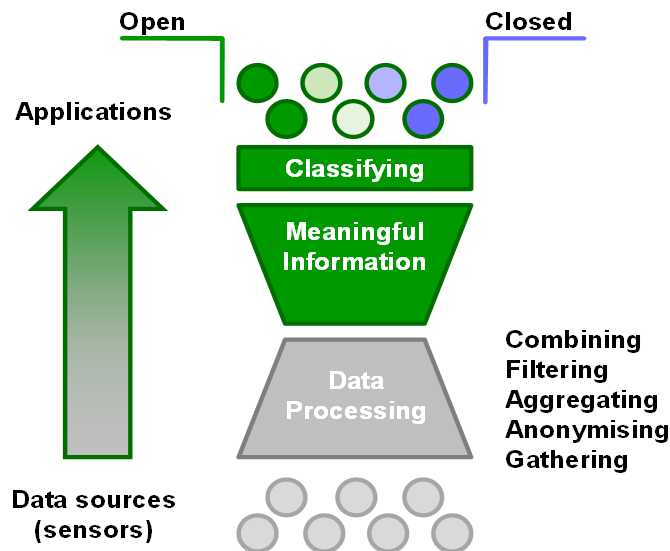
Figure 1.2: High-level transition process from data to information

ious types of street furniture, that could be adapted to house sensors in a way that is both easy to maintain, vandalism proof and visually appealing to the public. One of the candidates to house sensors is the lamp post, as they are widely spread across the city and are connected to the local power network. The first prototypes of lamp posts offering the ability to mount sensors are currently under development, for example in [17]. But several other types of street furniture could be used to house sensors as well. An analysis regarding which types of street furniture can be used to house a specific sensor type will prove helpful in the deployment of sensors and chapter 3 briefly touches upon this issue.

Essential in the operation of a sensor network is the ability of the sensors to transfer their measurements to systems that can act on these measurements. Sometimes, these systems will be located at the same geographical position as the sensor itself, making this problem relatively easy to solve. But usually some form of central storage or analysis of city wide measurements is desired, leading to the requirement for a data connection with appropriate specifications for each sensor. As each type of sensor or cluster of sensors generates a characteristic amount of data, varying from extremely small amounts (few bits per day) to thousands of kilobits per second, the network infrastructure has to be designed according to various technical requirements to be able to handle this diverse traffic pattern correctly. The broad range of connectivity options available at the moment is both a beneficial asset and a complicating factor in designing a network connecting a wide urban area. Figure 1.3 shows a variety of access technologies that is currently available in the urban public space on a nation wide scale [46], connecting both people and IoT devices.
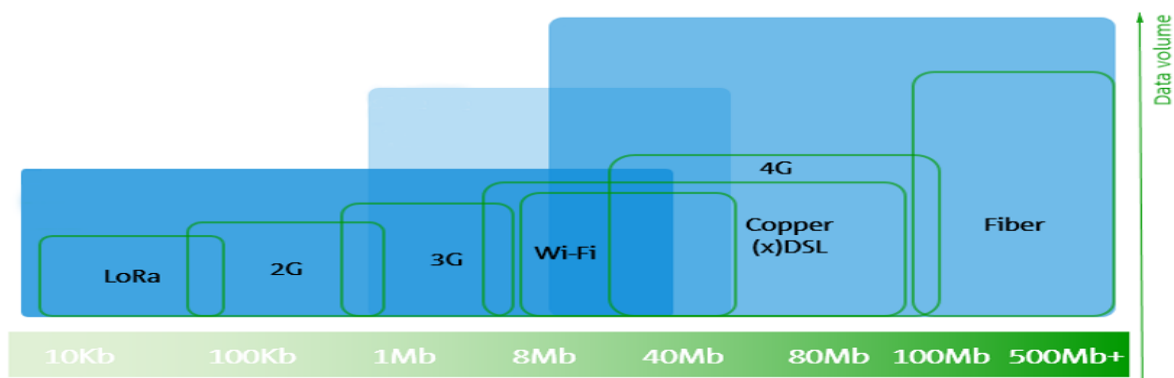
Figure 1.3: Overview of access technologies indicating the available throughput and data volume

Research [48] has shown that the portion of devices in the Internet of Things that will be connected through a cellular network is only a fraction of the total amount of connected devices. Other devices will likely connect using technologies like Bluetooth, ZigBee, Wi-Fi or other local (ad-hoc) connectivity solutions that are not managed by an operator. It is therefore necessary to design an architecture that enables operators to incorporate local data streams into their network in a way that is cost-efficient, flexible and secure. One of the main challenges for operators will be to position themselves in the new Internet of Things ecosystem that emerges in cities and rural areas all over the world. Some telecommunication analysts predict [3] that the traditional role of operators, providing connectivity to and between devices, although still necessary, will no longer be the most valuable service component in future propositions (an estimate of revenue distribution by [3] is shown in figure 1.4). It is therefore of utmost importance that operators develop solutions that add value to their existing (connectivity oriented) portfolio in order to ensure business continuity.
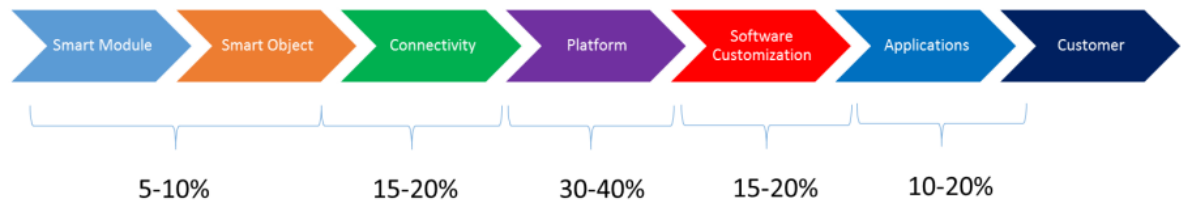
Figure 1.4: Estimate of the share of value in the total Internet of Things ecosystem

1.2. Research gap

Although the related concepts of the Internet of Things and Smart Cities are currently receiving attention of the scientific community as well as the industry [1], no actual guidelines or framework can be found for connecting a set of sensors in the urban public space in a cost-efficient way using existing telecommunications access technologies. Furthermore, due to the size of a large city and resulting fragmentation within the municipal organisation, determining the integral sensor necessity across departments has proven difficult.

The main contribution of this thesis lies in the identification and quantification of relevant sensor types for use in urban public spaces in the Netherlands. Furthermore, a contribution to the problem of optimising connectivity between different types of sensors and the existing telecommunication network in the urban public space is made using real data to optimise the results. To the knowledge of the author and the experts involved during the research design, this optimisation has never been done before.

1.3. Research questions

The connectivity optimisation problem discussed in the problem statement and research gap has been translated into three research questions.

RQ 1 Which types of sensors are promising, now and in the future, for a Dutch municipality like The Hague?

RQ 2 What types of telecommunication access technologies are currently available to support the connection of sensors in urban public space?

RQ 3 Given an amount of sensors of different types and requirements, what is the cost-optimal way of connecting them using existing telecommunication access technologies?

1.4. Research goals

This thesis aims to contribute to the situation outlined in the problem statement by providing an inventory of available sensors types, investigating the means to mount these sensor types to the available items of street furniture in the city and determining optimal placing of sensors for different city areas. The results can assist operators and municipalities in making well-considered choices for the roll out of new networks capable of providing connectivity to variety of devices in an urban environment. Additionally, combining the knowledge obtained from the sensor deployment analysis, a so called *data grid* can be calculated that shows the expected amount of data that will originate from different parts of the city generated by the deployed sensors. Operators can use this information to accurately scale and plan future networks upgrades.

This thesis explores the possibilities of using existing telecommunication access technologies, both wireless and wired, in connecting sensors in public space. In order to do this, an inventory of sensor types and their requirements is made for the Dutch municipality of The Hague. In addition, a selection of promising telecommunication access technologies in The Hague is made that could be used to connect sensors in a wide area. In order to match the selected sensor types to the telecommunication network, a cost-optimisation model is proposed describing the relevant properties of sensors and telecommunication nodes to be able to match supply and demand. The model incorporates the combinations of sensors, sensor types and telecom access technologies that are available in the geographical area of The Hague. Using proprietary datasets from KPN, a geographical optimization of sensor placing, telecommunication links and sensor network topology is performed so that the resulting network can be constructed and operated in a cost-optimal way.

1.5. Methodology

This section describes this thesis' research design and lists its sequential steps. Because the research questions cover a broad problem with many different aspects (either technical / engineering or exploratory / inventorying), the chosen methodology implies a customised approach per research question.

The research project started by defining an initial research scope consisting of eight research questions. The nature of the research required cooperation from actors in local government as well as in the telecommunications industry to provide data and contribute to interviews and expert sessions. Because the research has been carried out in The Netherlands, the largest Dutch telecommunications operator, KPN Royal, has been approached to contribute to the technology perspective of this research. KPN Royal operates both a mobile and fixed telecommunications networks covering the entire area of The Netherlands, and its portfolio provides the complete throughput range in figure 1.3. For these two reasons, KPN Royal is assumed to be representative for the current commercially available technologies in the urban public space.

To obtain insights into the functioning and requirements of local governments, The Hague municipality has been approached to cooperate with this research project. The reasons for choosing the city of The Hague as an object of study are twofold. First, the city is the third largest city in The Netherlands and therefore contains a variety of area and road types that can be used for the deployment of different sensor types. This allows for a more complete picture of the urban public space than would be possible with a smaller city. Second, the city is actively exploring possibilities for Smart City applications and is prepared to invest in them, both in terms of cost and human effort. A final contributing factor to the cooperation of The Hague municipality in this research is the existence of a Smart City research covenant between TU Delft, The Hague municipality and KPN Royal. Part of this thesis' initial scope included a settlement between the stakeholders TU Delft, KPN Royal and The Hague municipality regarding sharing the confidential parts of this thesis. A non-disclosure agreement was signed applicable to the proprietary and confidential parts of the data used during the research.

Halfway the project, a re-scoping has been performed based on feedback from academic supervisors. Due to time constraints and the need to reduce the projects' complexity, the power network layer has been excluded from the cost-optimisation model. Additionally, the focus of the research has concentrated on three of the initial eight research questions.

The approach followed for each of the three research questions has been as follows. Research question 1 covers the inventory and selection of sensor types suitable for deployment in the urban public space. Most of the findings related to research questions 1 have been obtained through discussions and interviews with municipality experts and suppliers of street furniture equipment. Results from the sensor pilot in the Zichtenburg area of The Hague have contributed to insights into the practical functioning of the selected sensor types. A literature review was performed to compare the obtained insights and answers from The Hague municipality with several other Smart City initiatives around the world.

Research question 2 involves the inventory and selection of wired and wireless telecommunication technologies for the connection of sensors in the urban public space. Answers to this research question have been found mainly through literature review and interviews with KPN experts. Additionally, a quantitative analysis of performance characteristics of the access technologies has been carried out to determine their suitability for transporting sensor data.

For research question 3, an interdependent network model has been designed incorporating the existing telecommunication networks in the urban public space, the requirements of the selected sensor types and the properties of the resulting telecommunication links. This model can be used to perform a cost optimisation for the location of the sensors and the type of dependency links between sensor nodes and telecom nodes. A detailed description of the cost-optimisation model and is discussed in 4. An implementation of the cost-optimisation model in MATLAB is used to run simulations resulting in cost-optimal placing of sensors, access points and access technologies. The parameters in the cost optimisation model, that will be discussed in detail in section 4.1 together with the simulation strategy, can be adjusted according to the results from research questions 1 and 2. Part of the process of designing the simulation tool has been to inventory and assess available data sources, both open and proprietary.

Sequentially, the steps taken for this research are shown in figure 1.5.
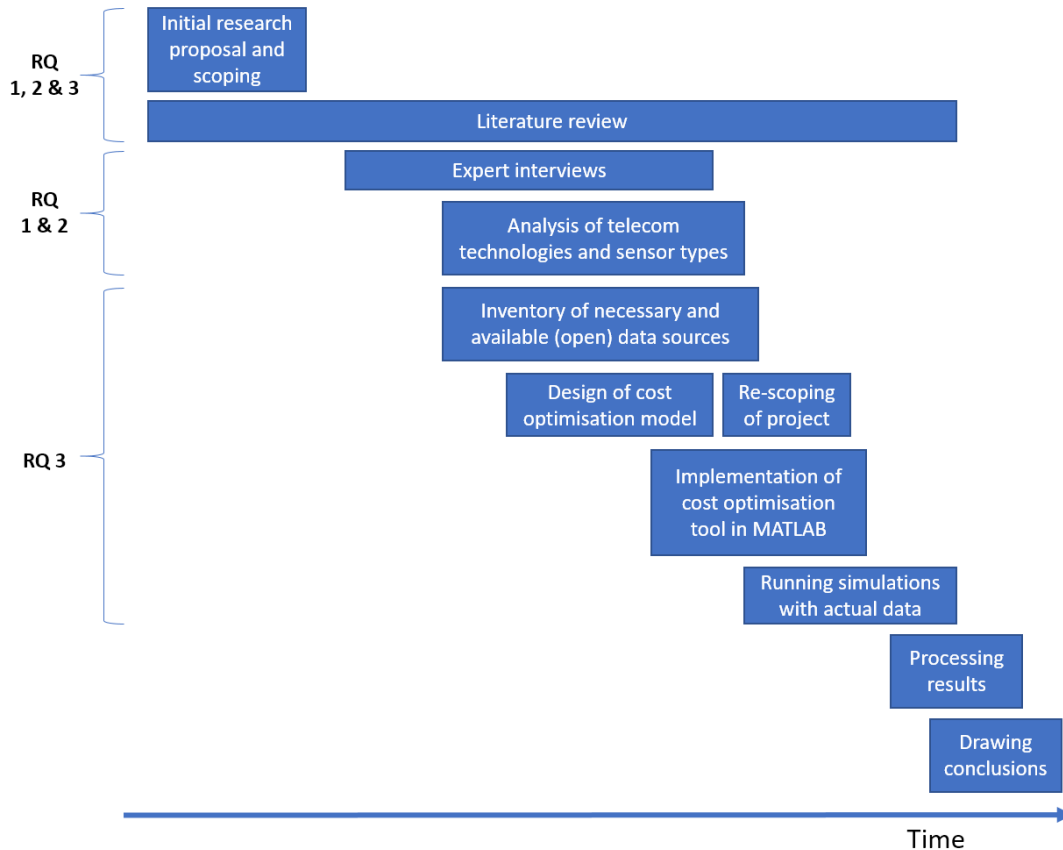
Figure 1.5: Methodology and sequential steps

1.6. Structure of the thesis

The thesis is structured as follows. Chapter 2 provides a literature review and discusses the definitions of key terminology related to sensors, interdependent network theory, applications of these two in the municipal public space within the larger context of Smart Cities and the Internet of Things.

Chapter 3 is concerned with the application of the interdependent network theory to the specific case of The Hague municipality. This chapter focuses on the selection of sensor types to be used for the remaining part of the thesis in section 3.2, partly based on the interview reports in Appendix A, together covering research question 1.
This chapter also includes an analysis of the available telecommunications access technologies that are currently available to support the deployment of sensors in public space in sections 3.3 and 3.4, covering research question 2.

Chapter 4 discusses the cost optimisation model that is created to optimise sensor connectivity in the public space in section 4.1. Furthermore, an implementation of this model in a simulation tool is described in section 4.2, including the strategy for performing the simulations and the required steps. The used data sources to perform the simulations are given in section 4.3.

Chapter 5 presents the results of the simulations performed with the simulation tool in the city of The Hague in section 5.1. Additionally, based on the simulation results, an estimation of the data production due to sensors for the city of The Hague is given in section 5.2. This chapter, together with the cost optimisation model discussed in chapter 4, covers research question 3.

Chapter 6 summarises the answers to the research questions in section 6.1 and provides recommendations to operators and municipalities wishing to deploy sensors in the urban public space in section 6.2. Finally, some directions for future academic and applied work are suggested in section 6.3.

2

Interdependent networks in the urban public space

As stated in chapter 1, the main focus of this thesis is connectivity for sensors deployed in the urban public space. This chapter elaborates on the definitions of key terminology and discusses the related literature providing the foundation for the chapters hereafter.

2.1. Sensors

2.1.1. Definition

The literature provides several definitions of the term *sensor*. In general, a sensor is an object or device that reacts to changes in the quantity, property, or condition that it is *sensitive* for by providing an output signal that changes accordingly. This output signal is by definition electrical:

> *A sensor is a device that receives a stimulus and responds with an electrical signal* [30]

The definition of a sensor given by [14] adds the concept of quantifiability:

> [A sensor is] *an element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured* [14]

For sensor output to be useful and comparable, it is necessary to be able to express the obtained quantity in a standardized unit. There are several systems in use that allow the standardized expression of quantities, the most important one being the *International System of Units* or *SI* [75]. Once sensor output is quantified using a units' system, it becomes a measurement. Measuring is defined by [117] as:

> *Measuring is the process of empirical and objective assignment of numbers to properties of actual objects or events, in such a way as to describe them* [117].

Because the terms stimulus, phenomenon, body or substance used in the definitions above need not to be electrical, sensors are sometimes classified as a specific type of *transducer*. A transducer is defined as

> [A transducer is] *a converter of any one type of energy into another* [30].

The reverse operation of a sensor can be performed by an actuator, which is also a type of transducer. The purpose of an actuator is to convert an (electrical) input signal to another form of energy with the intent to influence the environment. Sensors and actuators are often combined in systems together with a control function that can drive the actuator based on the sensor output, as illustrated in figure 2.1. An example of a system that combines sensors and actuators is a heating system. A user sets the required temperature in the
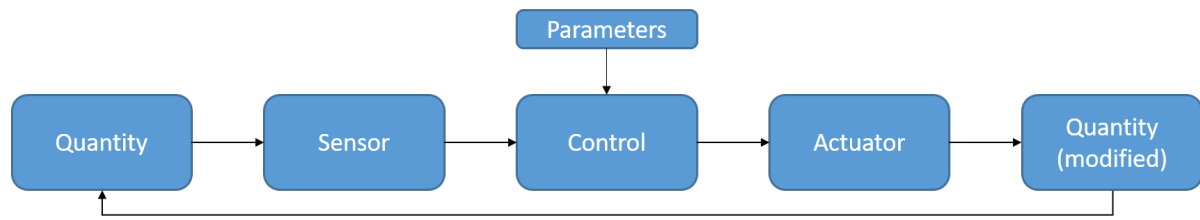
Figure 2.1: System using sensors and actuators to influence a quantity

room, and the current temperature is measured by a sensor in the room. The control function then decides whether the current temperature equals the required temperature and drives the heating in the room in order to correct any deviation from the user input.

In this thesis, a wider definition of the concept of a sensor is used, that includes objects or devices that can perform more complex operations. For example comparing a measurement with a threshold, aggregating or processing of signals are allowed to be performed inside the sensor. This leads to the modified scheme in figure 2.2. Processing of signals inside the sensor can reduce the amount of data that needs to be sent to the control function, which is especially beneficial if the geographical distance between the sensor and control function is large. This definition also allows to define sensors that measure more complex phenomena that are not directly expressible in SI quantities, for example because they require more than one input quantity to generate a (combined) output.
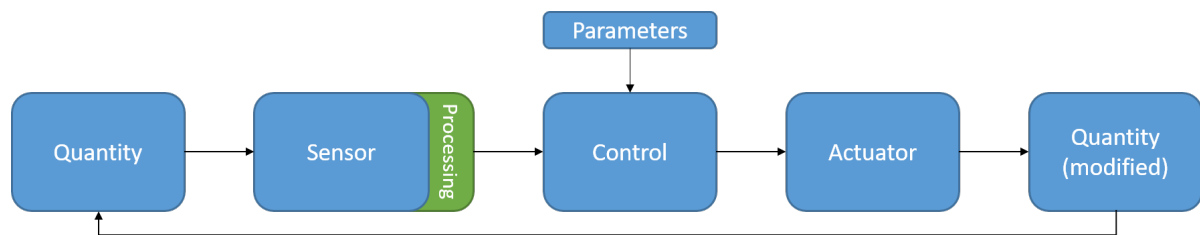
Figure 2.2: Extended system using sensors and actuators to influence a quantity

2.1.2. Sensor types

As the number of measurable properties of real world objects and phenomena is virtually unlimited, the number of different sensors available becomes extensive. Classifying sensors into sensor types can be done from multiple perspectives [30]. A distinction can be made based on the function of the sensors, e.g. measuring temperature or measuring pressure. This classification results in the sensor types *temperature sensor* and *pressure sensor* respectively. Another possibility is to classify sensors based on the means of detection of the quantity, e.g. electric or electromagnetic. Temperature, for example, can be measured using a direct contact thermocouple, or by taking advantage of electromagnetic radiation at a distance using a pyrometer. These sensors would be classified as electric sensor and radiation sensor respectively when using this classification system.
In this thesis a classification based on sensor function is used. One such classification together with example sensor types is given in [116], which is included in this document as appendix C as well. Here over 300 different types of sensors are listed that can be used for a wide variety of use cases.

In chapter 3 it is determined which sensor types are currently deployed in the urban public space and which types will likely be relevant for use in the future.

2.2. Interdependent networks

The theory of complex networks is concerned with the study of (real world) networks that do not follow one of the previous established theories in network science such as the Erdös and Rényi random graph model or a lattice structure [72]. Real world complex networks often show a degree distribution that has the form of a power-law. In a power law network, P(k), the fraction of nodes in the network with degree k, follows the relation

$$P(k) \sim k^{-\gamma}$$

which leads to a degree distribution as shown in figure 2.3. The parameter γ depends on the type of network (for real world networks this value typically lies between $1 < \gamma < 3$ [12] [102]). It has been shown by [104] that KPN's core telecommunication network in the Netherlands can be classified as a complex network. Also, a national economic network comprising all sectors follows a power law distribution [102].
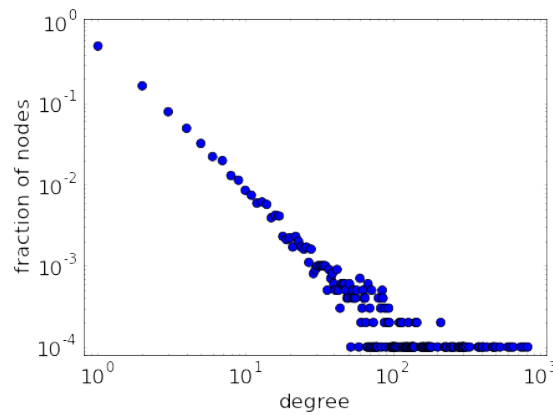
Figure 2.3: An example of a power law degree distribution observed in a network with 10.000 nodes and $\gamma = 2$. [67]

In practice, many real world complex networks depend on other networks in order to function correctly. An example is the dependency of a digital communication network on the power network. As the power network is nowadays also dependent on a communication network for monitoring and control, these networks are said to be interdependent. What distinguishes interdependent networks from single networks is the existence of two qualitatively different kinds of links: connectivity links and dependency links [25]. Connectivity links connect nodes within the same network whereas dependency links express the need for support from a node in another network. This dependency can be, but does not necessarily have to be, mutual.

Because the telecommunication network is geographically bound to a service area (determined by cables, street cabinets, exchanges), as is the power network, these networks can be classified as spatially embedded interdependent networks [25]. Spatially embedded networks have the property that the cost of their links increases with the physical distance between the nodes. This results in a network topology that is different from random networks, and to an optimization problem when it comes to connecting new nodes to the network [113].

Dependency links can be expressed using a dependency or interconnection matrix [112], B. When a network G_1 is described by an adjacency matrix A_1 ($N \times N$) and another network G_2 by an adjacency matrix A_2 ($M \times M$), a combined $(N + M) \times (N + M)$ adjacency matrix A

$$A = \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix}$$

can be created that is composed of the individual adjacency matrices. The dependency matrix can now be defined as
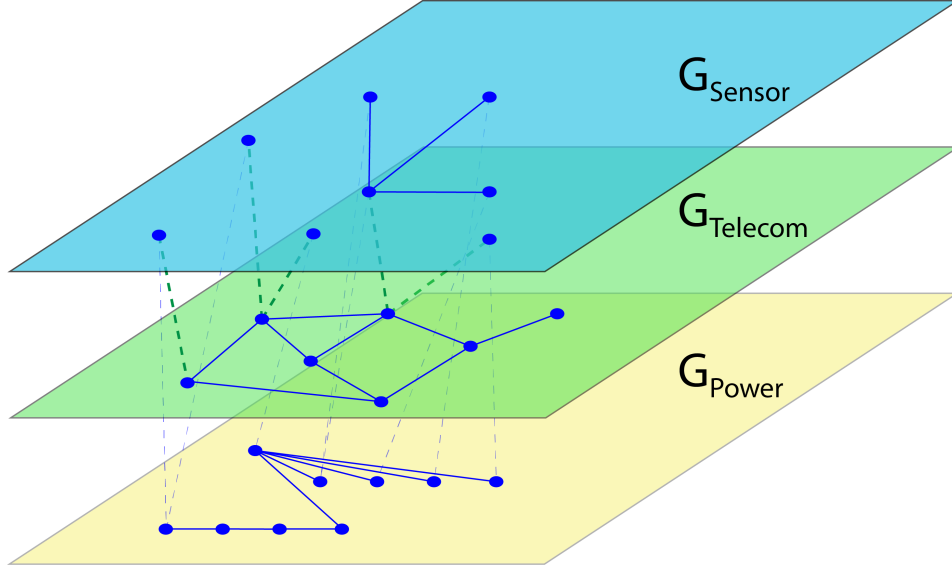
Figure 2.4: Three interdependent networks shown schematically. Each individual network consists of nodes and links, but some of the nodes in a network can have dependency links to nodes in another network (shown as dotted lines).

$$B = \begin{bmatrix} 0 & B_{12} \\ B_{12}^T & 0 \end{bmatrix}$$

which is valid for bidirectional dependency links. In the case of unidirectional dependencies, i.e. $B_{12} \neq B_{21}$, the definition becomes

$$B = \begin{bmatrix} 0 & B_{12} \\ B_{21} & 0 \end{bmatrix}$$

Figure 2.4 exemplifies three networks. Each of the networks is connected to every other network by means of dependency links between some of the nodes in the network. The A and B matrices can in this case be extended to include three networks.

In this thesis, two interdependent networks are of interest. First, a sensor network G_{Sensor}, consisting of sensor nodes and possibly direct communication links between the sensor nodes. Second, a telecommunication network $G_{Telecom}$, consisting of telecommunication access nodes and links between the nodes. The telecommunication network also has links to backhaul network nodes, but these are excluded from the research scope. When referring to the telecommunication network, solely nodes and links belonging to the *access* part of the network are considered. As stated in section 1.5, the power network G_{Power} shown in figure 2.4, although initially within the research scope, has been excluded for reasons of time and complexity.

Having discussed relevant interdependent network theory, research question 3 can now be formulated as an allocation of dependency links (b_{ij}) using least total link weights (w_{ij}) connecting nodes in G_{Sensor} to nodes in $G_{Telecom}$. This means that the dependency matrix B needs to be chosen such that the total cost of connecting nodes in G_{Sensor} to nodes in $G_{Telecom}$ is minimum. The total cost C should therefore satisfy the equation

$$C = \min \sum_{i,j} b_{ij} \times w_{ij}$$

Where C represents the total cost of all dependency links, the matrix W indicates the link weights assigned to the dependency links and B is the dependency matrix indicating the dependency links between G_{Sensor} and $G_{Telecom}$. The optimisation needs to satisfy the following constraints:

$$\sum_i b_{ij} = 1$$

Meaning all nodes in G_{Sensor} should have a single dependency link to one of the nodes in $G_{Telecom}$.

$$\sum_j b_{ij} \geq 0$$

Representing the fact that a single node in $G_{Telecom}$ can have connections to multiple nodes in G_{Sensor}.
In chapter 4 further details about the optimisation problem and strategy are discussed.

The main reasons for using an interdependent network model to solve the optimisation problem lie in the different nature of the nodes and links in the two involved networks. First of all, sensor nodes are assumed to be one of three types of nodes:

- a data generating node capable of connecting via a non-IP based protocol like ZigBee

- a data generating node capable of connecting via IP only

- a data generating and data-relaying node capable of connecting via both non-IP based protocols and IP, therefore acting as a gateway between these two types of links

In contrast to sensor nodes, telecommunication nodes are in this model assumed to be only consuming data. They consist of nodes that, although supporting different physical layer technologies, are all capable of communicating via IP. The fact that some sensor nodes cannot directly connect to a telecommunication node, prevents them from being part of one single network. The interdependent network model allows for making a distinction between the capabilities of sensor nodes and telecommunication nodes. Furthermore, the optimisation only concerns the sensors nodes, the telecommunication nodes are all assumed to be fixed and cannot be moved or change topology. Organising the sensor nodes in a network separate from the telecommunication nodes makes this distinction more explicit and the optimisation practically more feasible because the two types of nodes cannot be interchanged during optimisation. Finally, the two networks are operated by different parties that only have control over their own nodes. Information about the nodes and changes concerning the nodes only affect the individual networks when no interconnection links have been allocated.

2.3. Urban public space in the Netherlands

The sensors and sensor types in this research are specifically intended for use in the urban public space. This section discusses the characteristics of the urban public space and the different types of (public) areas that exist within an urban environment.

The terms and definitions used in this section mainly originate from Dutch governmental organisations and are specific for the situation in The Netherlands. Therefore a proper English translation is not always available. Whenever an English translation may lead to confusion as to the exact meaning of the term, the original Dutch term is given in a footnote.

2.3.1. Definition

A definition for the term *public space* consists of multiple aspects. It is proposed in [57] that the classification of areas in terms of public and private can be done along three criteria:

- Accessibility; reflects whether a space is accessible by the general public or only to certain individuals or groups, possibly after paying an entrance or service fee

- Ownership; reflects whether the space is owned by the government (public) or private parties such as companies or individuals

- Inter-subjectivity; reflects whether the space facilitates interaction between those present

In this thesis, the classification of public space will be based on the first two criteria, accessibility and ownership. This definition has the advantage that it can be determined objectively based on data sources, without knowing the exact usage by people in practice. In addition, this definition better corresponds to the definition adopted by The Dutch cadastre, who defines public spaces within the *Basisregistratie Adressen en Gebouwen* (Register for Addresses and Buildings) as follows [69]:

> A public space is an outside space located within a single town that is designated by the responsible municipal body as such and that has been given a name.

This definition limits the scope to outside spaces, excluding (parts of) buildings that may be accessible to the public and owned by the government. The definition used by the Dutch cadastre does not mention the three criteria above, meaning that space does not have to be publicly owned or accessible in order to be regarded as public space by this organisation. The definition requires that the municipal council formally assigns a name to a specific space in order to be regarded as public space. This can lead to the situation that national highways or provincial roads are not officially considered public space unless the municipal council assigns a name to it. In this research however, a certain space is regarded as being public when it is outside, accessible to everyone without restrictions and owned by the (local, provincial or national) government. In practice, this definition mostly includes roads, squares, parks, playgrounds, beaches etc.

Statistics Netherlands (*Dutch: Centraal Bureau voor de Statistiek (CBS)*) defines an area as *urban* based on the address density in that specific area [109]. The address density is calculated as the amount of addresses within a circle with radius 1 kilometre around an address divided by the area of the circle and is expressed in addresses per square kilometre. Municipalities are classified by Statistics Netherlands based on the categories in table 2.1 [109]. Statistics Netherlands considers a certain area to be urban when the address density is 1500 or above. In this research, this definition is adopted.

Table 2.1: Classification of municipalities based on address density

Category	Lower limit	Upper limit
Very highly urbanised	2500	
Highly urbanised	1500	2500
Moderately urbanised	1000	1500
Little urbanised	500	1000
Not urbanised	0	500

2.3.2. Roads and area types

It is expected that the type of area or road within a municipality is affecting the type of sensors and the number of sensors that are to be deployed. For this reason, the cost-optimisation model discussed in chapter 4 takes into account the different area and road types available within a city.

The entire surface of The Netherlands is divided into the following 9 area types by Statistics Netherlands based on use, function or geographical properties in order to collect statistics.

1. Traffic area
2. Built area
3. Semi built area
4. Recreational area
5. Agricultural area
6. Forest and natural area
7. Internal waters
8. External waters
9. Foreign countries

Appendix B shows the classification that is used in more detail, including sub-categories. It must be noted that this classification is not solely meant for public spaces as private spaces are classified as well. Figure 2.5 shows the classification applied to the city of The Hague.

Roads in The Netherlands are classified using the *Duurzaam Veilig* functional classification system [94][103] designed to improve traffic safety. Each road is assigned one of three classifications:

1. *Stroomwegen* (literally: traffic flow roads); Roads designed for the handling of as many vehicles as possible at a high average speed. Often highways are classified as *stroomweg*, but regional roads are sometimes given this classification as well. Crossroads are usually implemented as grade-separated junction[1] to improve traffic safety.

2. *Gebiedsontsluitingswegen* (literally: area access roads); Roads designed for handling relatively large traffic flows while allowing exchange of traffic with lower classified roads.

3. *Erftoegangswegen* (literally: property access roads); Roads designed to allow access to properties and the exchange of traffic. All road users (motorists, cyclist, pedestrians) should be able to use this type of roads safely.

Roads belonging to one of these three classifications are supposed to meet certain criteria described in the standard [94]. In cases these three categories do not fully cover the differences in available road types, responsible authorities often use a fourth category. This category falls between *Gebiedsontsluitingswegen* and *Erftoegangswegen* and is called *Wijkontsluitingswegen* (literally: neighbourhood access roads). Although not officially part of the *Duurzaam Veilig* classification system.

---

[1]Dutch: Ongelijkvloerse kruising

	Agricultural area		Business area		Mining area		Parks and gardens	
	Airfields		Cemetery		Mining waters		Railway terrain	
	Allotment garden		Dumping ground		North Sea		Recreational area	
	Area for public facilities		Eastern Scheldt		Open dry natural terrain		Recreational waters	
	Area for social or cultural facilities		Forrest and natural terrain		Other agricultural area		Residential area	
	Bordering lake		Greenhouse area		Other internal waters		Retail, hotel and catering area	
	Build terrain		IJsselmeer/Markermeer		Others		Rhine/Meuse	
	Building site		Internal waters		Overnight recreational area		Road traffic terrain	

	Scrapyard
	Semi-build terrain
	Single day recreational area
	Traffic terrain
	Wadden Sea, Eems, Dollard
	Water reservoir
	Western Scheldt

Figure 2.5: Classification of area types by Statistics Netherlands

2.3.3. Street furniture

Street furniture are all objects deliberately placed in the public space that perform some function within that space. Sometimes also pieces of art or monuments are classified as street furniture. For example, a light pole is an item of street furniture because it is placed and maintained by the municipality and performs the function of illuminating the public space. In general, street furniture is designed with a specific goal in mind. Part of the transition towards Smart Cities is to intelligently combine functions that were previously assigned to different items of street furniture into a single one, in order to reduce investment and maintenance cost and increase the attractiveness of the public space. It has been proposed in the past to use items of street furniture for the deployment of ICT in the public domain [9]. Some types of street furniture are particularly suitable for the deployment of sensors, because they posses some favourable properties. For example, some types of street furniture provide a certain amount of height above the street level, provide a protective casing against weather conditions, are able to supply electric power or are located at strategic positions within the city centre. Table 2.2 gives an overview of part of the items of street furniture deployed in the city of The Hague, including a rough estimate of the involved quantities. This selection originates from the *Basisregistratie grootschalige topografie* [53], a national database describing the public space in The Netherlands using the *Rijksdriehoekscoordinates* system (see Appendix D for details).

Table 2.2: Overview of installed items of street furniture in The Hague

Type	Quantity	Type	Quantity
Lamp post	73.000	Letter box	450
Road sign	25.000	Playground equipment	400
Bicycle rack	22.000	Billboard	250
Underground garbage container[1]	7.500	Traffic control system[2]	250
Bench	6.000	Traffic bollard[3]	180
Parking meter	2.300	Phone boot	70
Bus shelter	700	Dynamic route information panel	60

2.3.4. Governmental organisations involved with urban public space

In the Netherlands, responsibility for urban public space and spatial planning is divided between several (local) governmental organisations, depending on the function, location and importance of the public space. The following organisations have a responsibility related to the urban public space

- National government
- Provinces
- Water boards[4]
- Municipalities

In general, a municipality is responsible for the entire public space within its borders. Excluded are the specific parts of the public space that are not publicly owned or maintained by another organisation. Examples include highways built on municipal territory or canals that fall under the responsibility of the province. Figure 2.6 gives an overview of all roads in the *Metropolitan Area Rotterdam Den Haag*[5], indicating which governmental organisation is responsible [103]. The majority of roads in the figure is maintained by the responsible municipality (green). Highways are maintained by the national government (red) and provinces (orange) are responsible for several roads in the area. A large number of roads is maintained by water boards (blue). The remaining part of the roads is owned by private parties (purple) or has an unknown owner (black). The sensor type analysis described in chapter 3 has been limited to the urban space that falls under the responsibility of the municipality.

2.4. Smart Cities and the Internet of Things

The topics described in the previous sections are interrelated. They are relevant within a broader context and are related to several trends that are visible within our society. This section elaborates on the concepts of the Internet of Things and Smart Cities that form the contextual embedding for the topics in this thesis.

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[1]Dutch: Ondergrondse Restafval Container (ORAC)
[2]Dutch: Verkeersregelinstallatie (VRI). It is possible for a single traffic control system to consist of multiple traffic lights.
[3]Dutch: Poller
[4]Dutch: Waterschappen
[5]Dutch: Metropoolregio Rotterdam Den Haag (MRDH)
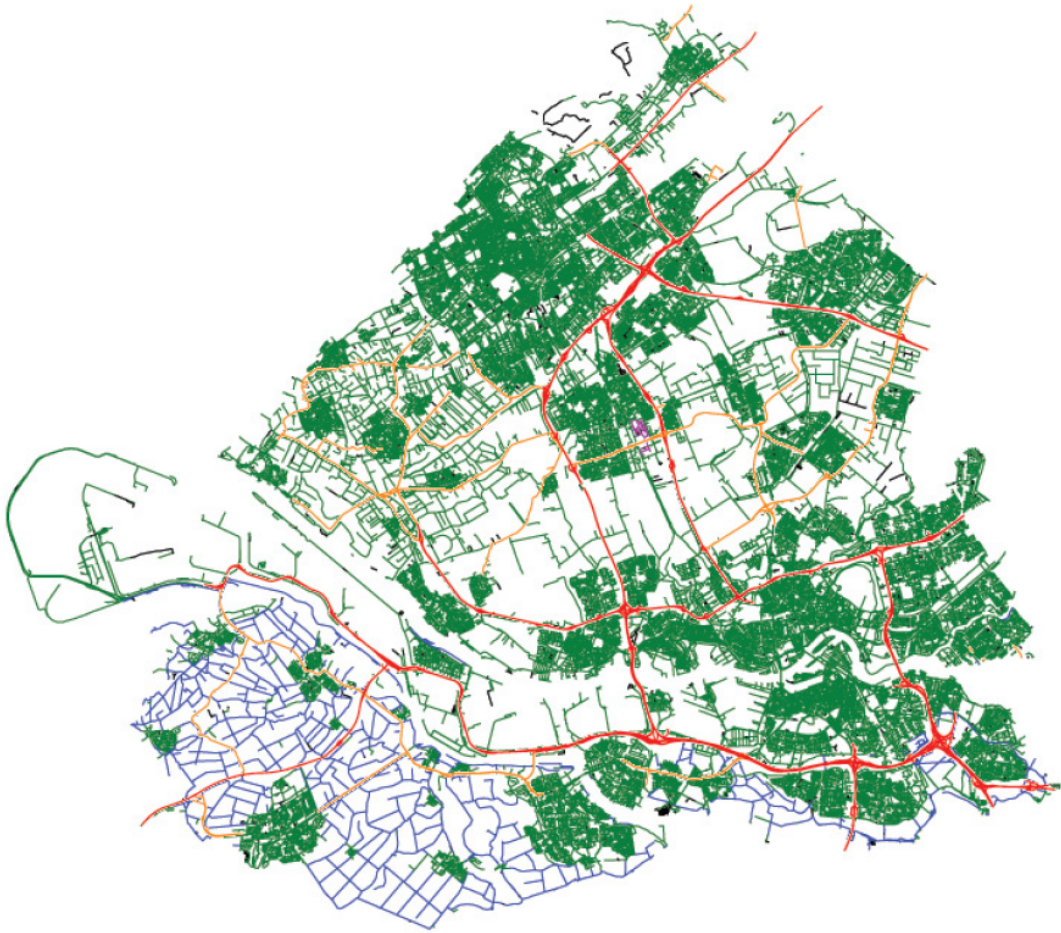
Figure 2.6: Map showing different responsibilities regarding roads in the Metropolitan Area Rotterdam Den Haag

2.4.1. Internet of Things

The term Internet of Things (IoT) originates from the 1990s [68] and was originally intended to describe the emergence of RFID tags in everyday objects. Currently, the term IoT comprises much more and is better described as a conceptual vision than as a single technology. This vision encompasses the belief that internet connectivity will extend to physical objects that previously did not have such a connection. Recent developments in technology end electronics have made the IoT vision more realistic, as sensors, connectivity and computing resources are becoming increasingly affordable.

The IoT is closely related to other concepts used to describe connectivity to things, such as the general term *Machine to Machine communication (M2M)* or *Machine Type Communication (MTC)* as more often refered to in relation to 3GPP technologies [6]. Some differences between the IoT and M2M are described in [45]. Regarding the business aspects of M2M and IoT, [45] observes that M2M is more often referred to as a solution for a specific business problem, involving a single stakeholder and using a single proprietary application or a single device (or device type). The used software and protocols are often very specific for the industry they are used in. IoT on the other hand, is considered to enable a more open *marketplace* using standard components and horizontal integration and innovation. Much of the added value comes from the combination of different data sources, applications and services from different parties through open standards and Application Programming Interfaces (API's). This is reflected by the definition used by the ITU for the IoT [50]:

> A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.

This thesis	ITU-T	Höller *et al.*	IDC
		Business	
Application	Application	Application	Applications/Vertical Industries
Data Analytics	Service & Application support	Data & Information	Analytics/Social Business
Data Management		Service Support	Platform
Connectivity	Network	Communication	Connectivity/Service Enablement
Device	Device	Resources	Intelligent Systems/Devices
		Assets	

Figure 2.7: Internet of Things domains comparison

This definition emphasizes the need for connectivity to things, but the IoT vision usually requires more components to be fully realised. In the literature, an Internet of Things *application* is often divided into domains or layers [49], each providing an essential function within the system as a whole. The number of different identified domains can vary, but usually between 4 and 6 domains are chosen depending on the grouping of functions. Often the functions management and security are considered separately, because they span multiple or even all of the domains.

In this thesis a 5 domain model is used, as is illustrated in figure 2.7 together with a reference to three other models. The ITU distinguishes four domains in their definition of the IoT [50], and adds generic management and security capabilities spanning all four domains.

The IoT as defined by IDC, a market research company, consists of five domains [49].

In [45], Höller et al. define the IoT using 7 domains. The main difference between this model and the former two is the addition of two domains, an *Assets domain* and a *Business domain*. The *Assets* domain represents real world objects and entities and the *Business* domain involves integration of the application into business processes and systems.

The domains that are distinguished in this thesis are:

1. Application

2. Data Analytics

3. Data Management

4. Connectivity

5. Device

It is essential to notice that these domains do not stand on their own. Data and information should be able to flow between the domains, with the proper security measures in place, preferably in a standardised way so to enable interoperability between different vendors. The following sections explain the different domains in more detail.

Device	Connectivity	Data Management	Data Analytics	Application
SIM sensor/actuator chip tag	fiber copper 2G/3G/4G Wi-Fi LoRa	Archiving Storage Data centers	Machine learning Data clustering Algoritmes	Information open closed
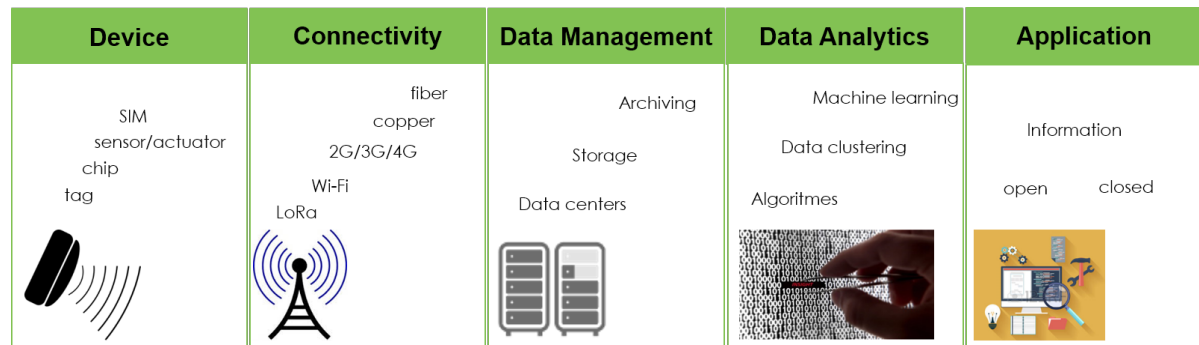
Figure 2.8: Internet of Things domains

Device

The Internet of Things frequently uses sensors as a fundamental building block for systems and applications. As opposed to the sensor-actuator system illustrated in figures 2.1 and 2.2, the role of sensors in the Internet of Things is in general not to directly influence a measurable quantity. Sensors are mainly used as the interface between the digital world and the physical world, to provide computational systems with required data about the status of physical objects.

Connectivity

Sensors need connectivity in order to transport their data within the sensor network and possibly further onto the internet. As sensor types differ in the amount of bandwidth and latency, both required for proper operation, likely different kinds of connectivity options are required to support a heterogeneous sensor network. Possible connectivity options for the Internet of Things will be discussed in section 3.3.

Data Management

The Data Management functions in the Internet of Things are responsible for collecting, storing, and archiving of data. Also, this function must ensure that proper *authentication*, *authorization* and *accounting* (AAA) is in place in order to protect the data from corruption and access by unauthorized individuals or organisations. It is typically located in a datacenter and has connections to both the connectivity layer and higher layers through standardised interfaces.

Sometimes the function of *device management* is integrated within this domain, although can be argued that this belongs to the connectivity domain. Device Management has the goal to keep track of all the different devices that are connected to the system. This is important to make sure that data from the sensors only gets to the right owner, to stop malicious devices from getting access to the data store and for billing purposes.

Data Analytics

The Internet of Things gets a significant part of its added value from data analytics, this is a key element that distinguished the IoT from classic Machine-to-Machine communication. Data analytics, sometimes called *Big Data* when large amounts of data are involved, is a science that involves studying data with the goal of extracting patterns, information and insights from it.

Applications

Applications are used to present the gathered data, information and conclusions to the end user and offer a way for the user to interact with the information.

Figure 2.9 shows a practical example of the division of IoT functionality in domains. This architecture has been developed within KPN in 2016 and shows the high level building blocks required to deploy an IoT application converting data from sensors into useful and accessible information [58].

When the IoT is used within cities to provide benefits for the citizens of the city itself, it can be considered to be contributing to a concept called *Smart City*, which will be discussed in the next section.
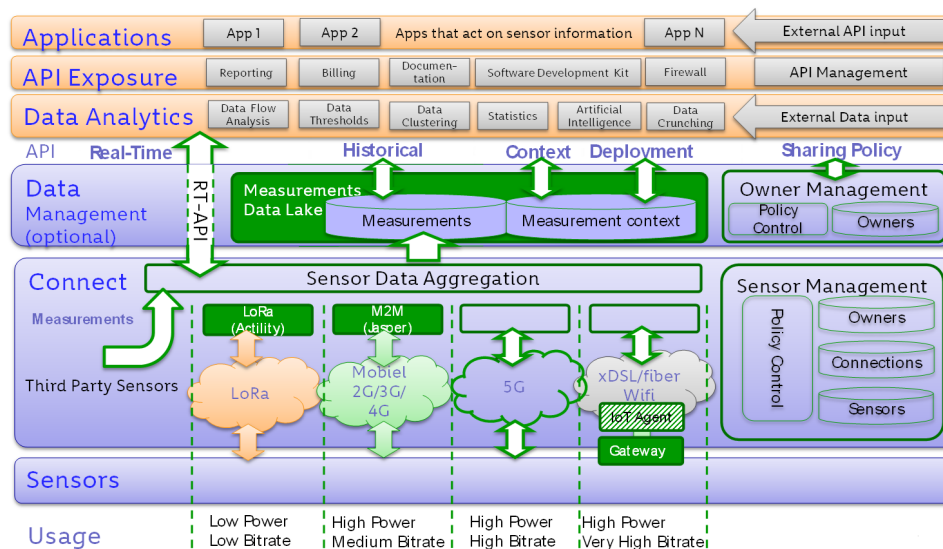
Figure 2.9: Internet of Things architecture from a sensor perspective developed within KPN

2.4.2. Smart Cities

The term *Smart City* has existed for some time in the literature, gaining steady popularity starting with the signing of the Kyoto Protocol in 1997 [24]. The Kyoto Protocol recognised the important role cities need to play in the reduction of CO_2 emissions and resulted in efforts to effectuate this policy. The term Smart City received little attention in subsequent years, but a new breakthrough came in 2010 with the publication of the *Europe 2020 Strategy* by the European Union that stimulated research in the direction of Smart Cities [101]. Despite the long history, providing a single definition capturing the full concept of Smart City is complicated, because of the broadness of the concept. Multiple definitions of what exactly a Smart City is have been given by several authors in the past. In general, the goal of becoming a Smart City is to improve the quality of life for its citizens in a sustainable way, and many authors emphasize the role of ICT to reach this goal. Multiple aspects play a role in the perceived smartness of a city, as can be observed from the definition given by [18]:

> A city can be defined as 'smart' when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance.

The definition given by [114] assigns a major role to ICT in the development of a Smart City:

> The use of ICT [makes] the critical infrastructure components and services of a city – which include city administration, education, healthcare, public safety, real estate, transportation, and utilities – more intelligent, interconnected, and efficient.

Work done by [37] yielded six characteristics of a Smart City, together with 31 factors contributing to these characteristics. Contributing factors to these characteristics are shown in figure 2.10. Together they are used to rank cities according to their smartness. The six Smart City characteristics are:

- Smart economy

- Smart people

- Smart governance

- Smart mobility

- Smart environment

- Smart living

SMART ECONOMY
(Competitiveness)

- Innovative spirit
- Entrepreneurship
- Economic image & trademarks
- Productivity
- Flexibility of labour market
- International embeddedness
- *Ability to transform*

SMART PEOPLE
(Social and Human Capital)

- Level of qualification
- Affinity to life long learning
- Social and ethnic plurality
- Flexibility
- Creativity
- Cosmopolitanism/Open-mindedness
- Participation in public life

SMART GOVERNANCE
(Participation)

- Participation in decision-making
- Public and social services
- Transparent governance
- *Political strategies & perspectives*

SMART ENVIRONMENT
(Natural resources)

- Attractivity of natural conditions
- Pollution
- Environmental protection
- Sustainable resource management

SMART MOBILITY
(Transport and ICT)

- Local accessibility
- (Inter-)national accessibility
- Availability of ICT-infrastructure
- Sustainable, innovative and safe transport systems

SMART LIVING
(Quality of life)

- Cultural facilities
- Health conditions
- Individual safety
- Housing quality
- Education facilities
- Touristic attractivity
- Social cohesion

Figure 2.10: Smart City characteristics and corresponding contributing factors

In [73], the relation between a Smart City and its characteristics, initiatives and projects is described. As can be seen in figure 2.11, initiatives projects and projects often contribute to more than one Smart City characteristic. This decomposition of the Smart City into initiatives and projects is useful to relate the concept of Smart City to the previously discussed concept of the Internet of Things. As projects provide concrete technological solutions contributing to the Smart City, this is the level on which the IoT can prove to be useful. An example relating an IoT based technological solution to a Smart City goal is given in figure 2.12, where the wish to contribute to the Smart Economy is translated to the technological enablers belonging to the Internet of Things.
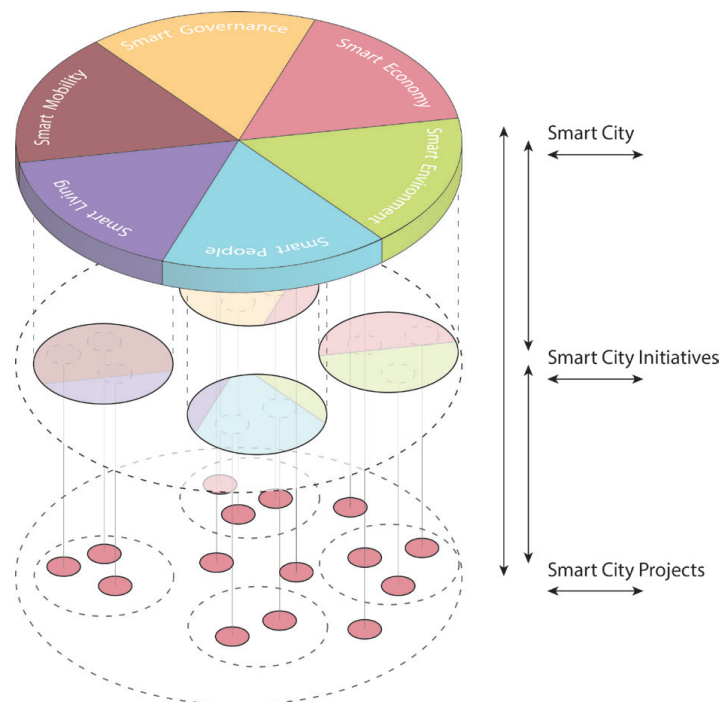
Figure 2.11: Smart City characteristics, initiatives and projects [73]
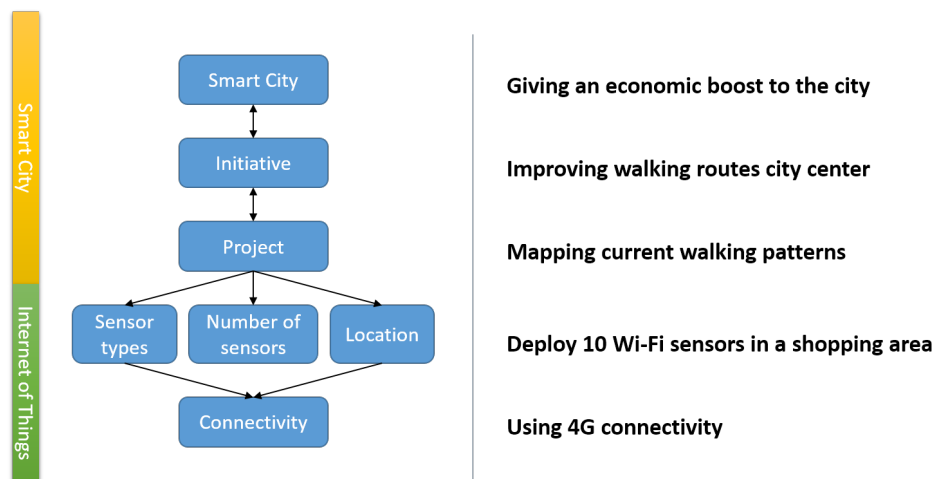
Figure 2.12: Smart City decomposition into projects and underlying Internet of Things enablers

2.5. Conclusions

Sensors exist in a wide variety of types and means of detection. By reacting to changes in the environment sensors produce an output signal. When meaning is given to the output signal using a units system, the output can be regarded as a measurement. Complex operations like data aggregation or signal processing can be performed on the output signals to make them more suitable for future use. The combination of sensor and processing will in the remaining parts of this thesis be referred to as sensor.

Interdependent networks are a way to model the relation and interaction between two separate networks. In this thesis, an interdependent network model has been chosen to describe the interaction between a sensor network and the telecommunication network in the urban public space with the goal of optimising the dependency links between the two networks.

A certain area can be classified as public based on multiple criteria. In this thesis a certain area is regarded as being public when it is outside, accessible to everyone without restrictions and owned by the government. The Dutch Central Bureau for Statistics classifies the total area of The Netherlands into categories based on usage, function or geographical properties, and calculates the level of urbanisation of a specific area. It is likely that the need for sensors and sensor networks differs between areas with different usage or level of urbanisation. This will be further discussed in the next chapter.

The Internet of Things is a term that describes the vision of internet connectivity extending to physical objects, or things. These objects can then use this connection to transfer data with other objects independent of a human operator. Section 2.4.1 discussed five domains that can be distinguished in an IoT application. When used in the context of the Internet of Things, sensors play an important role as a possible source of data. When sensor data is to be transmitted to a remote (central) control function, intelligent processing can be added to the sensor to reduce the amount of data that needs to be sent or to enable new types of measurements that are not possible with a single sensor.

Sensors and their function within the Internet of Things can play a central role in future Smart City applications. Smart City applications and projects are often trans-sectoral but always contribute to one or more of the Smart City characteristics in figure 2.10.

3

The Hague: Smart City applications and connectivity

This chapter explores the Smart City applications that have been identified for deployment in the urban public space and the sensor types that are required for their successful operation, providing an answer to the first research question:

> Which types of sensors are promising, now and in the future, for a Dutch municipality like The Hague?

In order to determine promising types of sensors, the city of The Hague has been selected as an object to study because it is representative for a large city and its Smart City needs. Results from the research performed in The Hague are then compared to other cities that have started to extend the use of sensors in the public space. As Smart City applications make extensive use of different sensor types with corresponding different requirements, the telecommunication technologies for connecting different sensor types are discussed and evaluated. The results of evaluating telecommunication technologies provides the answer to the second research question:

> What types of telecommunication access technologies are currently available to support the connection of sensors in urban public space?

3.1. The Hague

The Hague municipality contains the entire area of the city of The Hague, the third largest city in The Netherlands. Throughout its existance, the city aquired several former towns and municipalities, among which the seaside resort of Scheveningen [98]. It is inhabited by approximately half a million people spread across 44 districts [110]. The Hague serves as the seat of the national parliament and houses most of the foreign embassies and other international (justice) organisations, concentrated in the International Zone. Together with the city of Rotterdam and 21 other adjacent municipalities in the area The Hague forms the metropolitan area Rotterdam The Hague[1] with almost 2.3 million inhabitants.
Figures 3.1 and 3.2 show the position of city of The Hague within the *MRDH* and The Netherlands respectively[2].

3.1.1. Urban problems driving Smart City applications

Cities face several challenges and (urgent) problems that drive the emergence of Smart City applications in the public domain. The local government translates these challenges into policies and roadmaps that are

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[1]Dutch: Metropoolregio Rotterdam Den Haag (MRDH)
[2]Images adapted from *Overheid in Nederland*
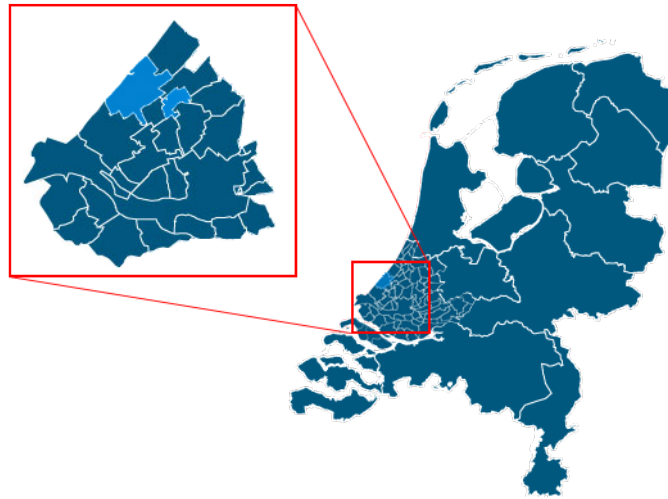
Figure 3.1: The Netherlands showing the location of the MRDH region within the province of *Zuid-Holland*
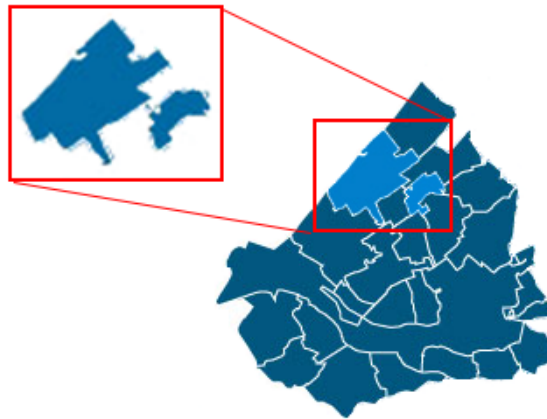
Figure 3.2: The city of The Hague within the MRDH region

discussed with the municipal council. One of these is the *Road Map Smart City Den Haag 2014* [41]. In this document, the priority for Smart City projects in the period until 2018 has been defined. The two most important topics identified are

- Quality of Life; This is a very broad concept, including many aspects of our everyday life and our surroundings. In [41], it is defined as being an attractive city for workers, citizens and visitors by optimising their living and working environment.

- Security; Because of the presence of many embassies and government organisations within the city, security is a priority for the local authorities. This has contributed to the foundation of The Hague Security Delta (HSD), a partnership between businesses, governments, and knowledge institutions with the goal of increasing knowledge and innovation in the field of cyber-security, national and urban security, protection of critical infrastructure, and (digital) forensics [26].

Interviews with municipal experts revealed that more urban issues may require the attention of Smart City projects. For example, the interviewee in appendix A.4 states that for Public Health Services in the region of The Hague (GGD Haaglanden) the following topics are a priority:

- Air quality; The location of the city of The Hague close to the North Sea causes difficulties in the management of traffic coming from and going into the city, because the construction of a ring road around the city is impossible. This results in large amounts of traffic going through the city, causing traffic jams

and air pollution. The Hague has some of the streets with the worst air quality in The Netherlands [86], and although air quality has been improving over the past few years, concentrations of some substances contributing to air pollution still exceed the European norm.

- Noise pollution; The amount of noise in a city could have an impact on the well-being of its citizens, especially during night hours. 25% of the citizens in The Hague experiences or has experienced noise disturbances during the night, as stated by the interviewee in appendix A.4. Better understanding of the sources of these disturbances allows to take appropriate and effective measures.

- City temperature; Due to the so-called *urban heat island effect*, air temperature within cities can be as much as 8 degrees Celsius higher than in the surrounding areas. This is especially harmful for elderly inhabitants. Quantifying the heat island effect for specific geographical locations within the city and being able to relate this to properties of the (built) environment can be a valuable asset in city planning and healthcare.

In one of the interviews in appendix A.3, it is noted that energy savings are an important priority for The Hague municipality. In order to comply with European legislation, public lighting has to become more energy efficient. In addition to the replacement of older equipment, a substantial part of the reduction in power consumption is expected to come from Smart City projects.

Another interview in A.3 revealed that The Hague municipality foresees the deployment of *small cells* in the public space on a larger scale. Small cells contain relatively small radio transceivers with limited coverage that can be deployed in areas where capacity, coverage or quality of existing mobile cellular networks is insufficient. Small-cell deployment has been going on for some time in the Netherlands [87], and with the introduction of 5G, the number of small-cells in the public (and private) space is expected to increase even further [79]. Often small cells are deployed in city centres, because of the large number of mobile users, unfavourable radio propagation conditions and lack of suitable locations for macro cells. The Hague municipality prefers to incorporate small cells into the existing street furniture wherever possible. Therefore, it seems like a logical next step to take future small cell deployment into account when connecting items of street furniture using telecommunication access technologies.

Having discussed some of the urban challenges that a city like The Hague is dealing with, section 3.2 discusses this thesis' analysis regarding the selection of sensor types that could possibly provide more insights into dealing with these challenges in Smart City projects.

3.2. Smart City sensor applications

Sensor technology serves the purpose of providing data. This can be data about anything as long as the technology is available to accurately measure it. Currently, data from various sources is already being collected via sensors in The Hague municipality, e.g. related to traffic flow and environmental monitoring. As The Hague municipality has the ambition to make the city of The Hague a Smart City [41], the need for additional (real time) data sources to support this ambition arises. This section explores existing and new sensor types that are expected to be deployed within the coming years. In order to obtain insights into the sensor requirements of the city of The Hague, interviews and interactive sessions with municipality experts have been performed (reports of these interviews are included in appendix A). Furthermore, the preliminary results of a pilot project in the area of Zichtenburg in The Hague have been shared with the covenant partners TU Delft and KPN and literature review into existing Smart City projects has been done.

To systematically determine what sensor types are being used and what purpose they serve, the survey inventory system in figure 3.3 is used during the interviews. A distinction is made between the data that is of interest to the sensor owner and the quantity that is measured by the sensor, expressed as *quantity description* and *what is measured* respectively. The example in figure 3.3 shows that this difference is of importance because the quantity measured by the sensor is often not directly of interest. Furthermore, information is collected about the location(s) where the sensors are being deployed, the physical object to which they are mounted, when they are in operation and how many of them are deployed. Finally also the purpose for the sensor deployment is considered.

	Quantity of interest	Sensor type	What is measured	Sensor location(s)	Mounting object	When in operation	Why deployed
Example: sensor type X	Number of people	Wifi/Bluetooth detector Camera	Wifi/Bluetooth MAC addresses Street image	Squares Shopping malls Tourist areas	Light pole Separate pole	Continuously	City planning Law enforcement

Figure 3.3: Sensor inventory system showing one example

3.2.1. Current deployed sensor types in the city of The Hague

Like The Hague, municipalities in The Netherlands already deploy sensor technology in their public space. The contemporary set of sensors owned by the municipality are primarily concerned with the control and monitoring of traffic. Other types of sensors that can be found are for environmental monitoring, but these are often managed by other organisations like the Royal Netherlands Meteorological Institute (KNMI), Netherlands National Institute for Public Health and the Environment (RIVM) or Netherlands Organisation for Applied Scientific Research (TNO). This is one of the reasons why it is hard to provide a full overview of the sensor types and the quantities currently deployed as there are many parties involved and not all are aware of the equipment installed by others. Inventoried in this thesis' research, the following eight sensor types were found within the borders of the city of The Hague.

- Air quality sensors
- Induction loop detectors
- Ground water level sensors
- Pneumatic tube detectors

- Radar detectors
- Speed cameras
- Weather stations
- Video cameras

In 2016, the current state of sensor technology in other parts of the MRDH has been investigated by [103]. This research includes results for the municipalities of Rotterdam, Maassluis and Westland and for the MRDH as a whole, including highways within the area managed by the national government represented by *Rijkswaterstaat*. Comparing the sensor types found in the investigated municipalities by [103] with the results from the inventory in the city of The Hague is the absence in The Hague, two difference arise. The city of Rotterdam use Automatic Number Plate Recognition (ANPR) cameras and Bluetooth detection equipment for the calculation of traffic travel times, two sensor types that are not yet actively used in the city of The Hague. When results from Rijkswaterstaat are included in the comparison, the differences include equipment for weighing of trucks (called *Weigh-in-motion*) and the use of road slippery detection sensors.

Generally, it is observed that the current deployed sensor types within the MRDH are primarily concerned with the Smart City characteristics 'Smart Mobility' and 'Smart Environment', as discussed in section 2.4.2.

3.2.2. Sensor type selection

Based on the discussed urban challenges in section 3.1.1, the set of existing sensor types in section 3.2.1 and the interviews with municipality experts, the list of sensor types in table 3.1 has been completed. This subsection provides a brief description of each sensor type.

Air quality sensor   This device generally consists of several sensor types that measure different quantities. Most common are sensors that measure NO_2, NO, O_3, PM_{10}, $PM_{2.5}$ and soot. In The Hague, there are around 3 to 5 locations where these sensors are deployed depending on temporary measurement campaigns.

Induction loop detector   This sensor type detects the presence of a vehicle in its vicinity by measuring disturbances in the magnetic field around a coil due to this vehicle. The windings of the coil are placed inside the road surface and connected to electronics by the side of the road. This sensor type is frequently used to alert traffic lights of an approaching vehicle or to count vehicles on a certain road section.

Garbage level sensor   This sensor type measures to which extent garbage bins are filled with garbage. The measurement is based on the distance between the sensor and the garbage and relating this distance to the height of the container to determine how much space is left. The distance can be measured using ultrasound pulses or laser pulses.

Ground water level sensor   This sensor type measures the ground water level at its position by using a perforated tube with a pressure sensor inside. The pressure sensor is frequently combined with temperature and air pressure sensors to correctly calculate the ground water level from the water pressure.

Sound level meter   This sensor type measures the sound level in its proximity. A microphone converts sounds into an electrical signal, that can then be used to calculate the sound pressure level expressed in dB. Because the decibel is a relative measure, it is determined relative to a reference value. Using sound level meters in an urban environment poses difficulties because determining a suitable reference value is not always easy.

Parking sensor   A parking sensor can be deployed inside the road surface or above the surface, and determines whether a vehicle is occupying the parking space. Known measuring methods are using infra red, radar, induction loop detection, optical recognition using video cameras or a combination of these technologies.

Pneumatic tube detector   This sensor type consists of one or two pneumatic tubes that are placed across the road, and detects the passing of bicycles or vehicles by measuring the pressure inside these tubes. Because the tubes are vulnerable for vandalism, this sensor type is usually deployed temporarily at a certain road section to count the number of bicycles or vehicles.

Radar detector   This sensor type is capable of detecting traffic by using electromagnetic pulses with high frequency. It is frequently used for alerting traffic lights or measuring vehicle speed, and sometimes also for counting vehicles. The exact technology used (Doppler, Pulse, Frequency Modulated Continuous Wave (FMCW)) determines the capabilities of the radar detector. Mostly Doppler radars are used, because they can reliably measure vehicle speeds and are less expensive compared to FMCW radars.

Speed camera   This is a photo camera that is triggered by another detector, usually radar detector, and makes a photograph of the licence plate of the triggering vehicle for law enforcement purposes. A similar type of camera can be used to capture vehicles driving past a red traffic light, although these are often triggered by induction loop detectors.

Temperature sensor   This sensor type measures temperature. Several measurement principles allow the measurement of temperature, depending on the application. For the measurement of air temperature, usually a Pt-500 resistance thermometer is used [56]. This type of thermometer has to be in direct contact with the object or substance of which the temperature has to be known. Temperature can be measured at a distance by exploiting the thermal radiation emitted by an object using a pyrometer.

Weather station   This is usually a combination of sensor types, often an anemometer, thermometer, hygrometer and rainfall sensor are included.

Video camera   This sensor type is used today primarily to allow human operators to observe the public space from within a control room. Modern camera types, together with software, are capable of reading license plates and calculate travel times or even determine parking violations and enforcing low-emission zone.

Table 3.1: Quantities of interest to the municipality and suitable sensor types

n	Quantity of interest	Sensor type	What is measured	Sensor location(s)	Mounting object	When in operation	Why deployed	Currently deployed in The Hague
1	Air quality	Combination of several types	Concentrations of CO, CO2, NOx, PM2.5, PM10	Locations of accelerating traffic / Locations vulnerable groups (schools, daycare)	Lamp post	Continuously	Improve public health	Yes
2	Air temperature	Resistance thermometer	Temperature	Open space	Lamp post	Continuously	Improve public health	Yes
3		Video camera		Main roads, crossroads	Lamp post	Continuously	Improve public safety	Yes
4	Ground temperature	Resistance thermometer	Temperature	Slopes, ramps, bridges	Lamp post / Road surface	Winter / Midsummer	Prediction of slipperiness / Optimising road salting routes / Detect melting tarmac / Detect expanding bridges/rail road switches	Yes
5	Ground water level	Pressure sensor	Pressure	Diverse locations	Dedicated perforated tube	Continuously	Research / Validate models / Evaluate policies	Yes
6	Garbage level	Ultrasound sensor	Distance from sensor to garbage	Location of garbage bins	Garbage bin / ORAC	Continuously (only transmit if full)	Optimise garbage collection / Prevention of litter	No
7	Number of people	Bluetooth receiver / Wi-Fi receiver	Smart phone broadcast signals	Diverse locations	Lamp post		City planning / Dynamic road signs	No
8	Sound level	Sound level meter	Sound pressure	Crowded locations	Lamp post	Continuously	Improve quality of life	No
9	Vehicle speed	Doppler radar / Induction loop / Laser	Speed	Near crossroads	Lamp post	Continuously	Improve quality of life / Assist law enforcement	Yes
10	Vehicle detection	Doppler radar / Induction loop / Pneumatic tube detector	Presence of vehicle	Near crossroads	Road surface	Between 6.00 and 22.00	Dynamic road signs, / City planning, / Evaluation of bicycle measures	Yes
11	Parking space occupation	Induction loop / Infra red	Pressence of vehicle	Crowded shopping areas / Disability parking spots	Road surface / Lamp post	Continuously	Prevent searching traffic	No
12	Water level on roads	Radar / Float switch	Water level	Storm drains / Inside tunnels	Road surface	Continuously	Detect sewer overflow / Detect tunnel flooding	No

3.2.3. Sensor pilot Zichtenburg

In order to meet the goals mentioned in [41] a pilot project has been started in the area of Zichtenburg, as depicted in figure 3.4[1]. This pilot project involves the testing of different types of sensors in an industrial area of the city of The Hague.

Figure 3.4: Location of the Zichtenburg area in the city of The Hague

In the Zichtenburg pilot setting, all sensor types have been deployed by 6 street furniture suppliers: Philips, Ziut, Elspec, CityTec, Tvilight and Smartnodes. Their responsibility extends to the data acquisition and data management of the generated sensor data as well. All sensor types, except the garbage level detector, are deployed in or at a lamp post in the area. Figure 3.5[2] shows the distribution of sensor types in the area. Every circle on the map denotes a lamp post, the color indicates the responsible supplier. The pilot involves 11 types of sensors, indicated by icons in the map.

3.2.4. Sensor data production

The Zichtenburg pilot yielded valuable insights into the amount of data that is produced by sensors in the urban public space. Table 3.2 lists the sensor types deployed in the pilot, and the amount of data that originates from them.

3.2.5. Sensor deployment scenarios

So far, results have been obtained for the relatively small Zichtenburg area in The Hague. An analysis has been made regarding the amount of sensors that would be necessary to cover the entire city of The Hague using the same set of sensor types as is used in Zichtenburg, supplemented with the sensor type video camera. For each of the listed sensor types in table 3.1, a minimum and a maximum number of sensors to be deployed in the entire city has been identified as shown in table 3.3. The figures in this table are based on a number of assumptions and estimates subject to uncertainty, hence the large spread between minimum and maximum for some of the sensor types. Table 3.4 describes the assumptions underlying the quantities in table 3.3 that have been identified together with experts from The Hague municipality.

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[1]Image adapted from Google Maps
[2]Image adapted from The Hague municipality
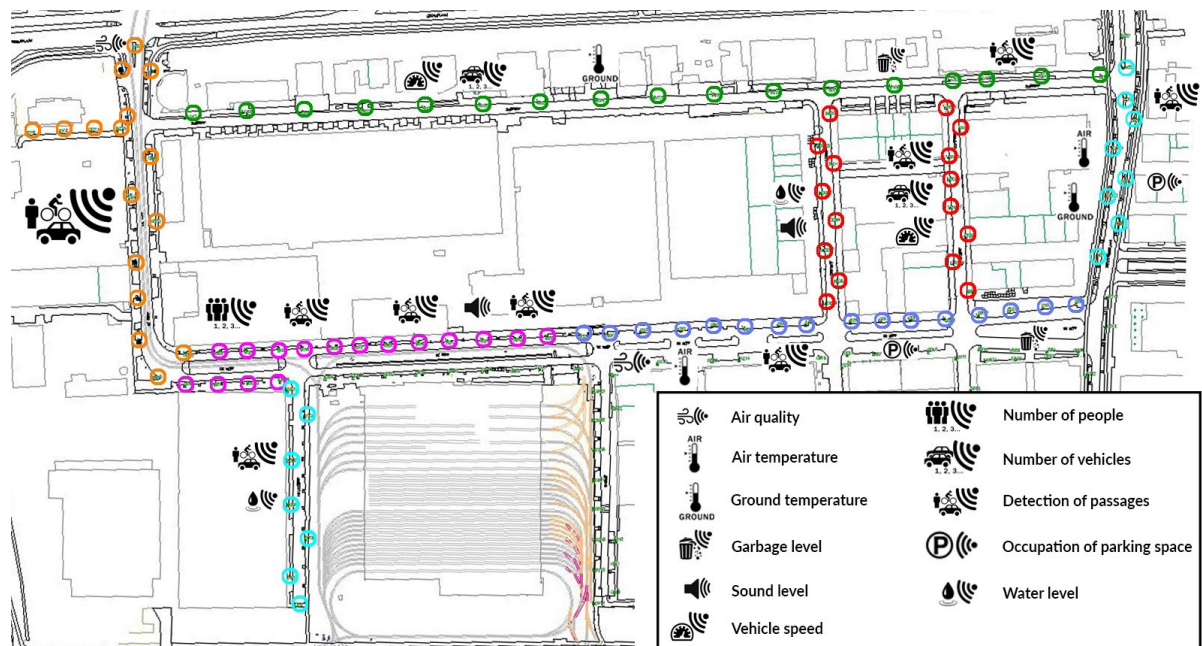
Figure 3.5: Different sensor types used in the Zichtenburg pilot

(a) Air quality sensor (top, with solar panel) together with a motion sensor (below) mounted on a lamp post

(b) Wi-Fi receiver mounted on a lamp post

Figure 3.6: Example of two sensors deployed in Zichtenburg pilot area

Table 3.2: Data production per sensor type in the Zichtenburg pilot

n	Quantity description	Data per measurement (Byte)	Measurement frequency
1	Air quality	10-50	1/5 minutes
2	Air temperature	10-50	1/5 minutes
3	Detection of passages	10-50	1/5 minutes aggregate
4	Garbage level in container	10-50	Event driven
5	Ground temperature	10-50	1/5 minutes
6	Number of people	10-50	1/5 minutes aggregate
7	Number of vehicles	10-50	1/5 minutes aggregate
8	Occupation of parking space	10-50	Event driven
9	Sound level	10-50	1/5 minutes
10	Vehicle speed	10-50	1/5 minutes aggregate
11	Water level on roads	10-50	1/5 minutes

Table 3.3: Minimum and maximum scenarios for the different measurement quantities in the city of The Hague

n	Quantity description	Minimum scenario	Maximum scenario
1	Air quality	200	800
2	Air temperature	25	50
3	Camera	1.000	1.500
4	Garbage level	300	7.000
5	Ground temperature	500	1.000
6	Number of people	40	80
7	Number of vehicles	2.000	4.000
8	Parking space occupation	450	675
9	Sound level	7	10
10	Vehicle speed	200	300
11	Water level on roads	50	150
	Total	4.772	15.565

Table 3.4: Sensor deployment rules underlying the quantities per sensor type

n	Sensor deployment rule minimum scenario	Sensor deployment rule maximum scenario
1	The estimate for this sensor type is based on locations of schools and daycare. Starting with 25% of the schools being monitored leads to the minimum scenario.	Taking into account all locations of schools leads to the maximum scenario.
2	The Hague uses the term Hotspot to identify locations where large numbers of people frequently come together. Five of these Hotspots are taken into account, each requiring 5 sensors of this sensor type.	Taking into account locations not marked as Hotspot
3	Placing of this sensor type is primarily expected at crossroads. Starting at the most important crossroads (currently 250 equipped with traffic control installations) and the requirement of unobstructed view in every direction leads to the estimate of 1000 sensors.	A margin of 50%.
4	The minimum scenario takes into account the currently deployed underground garbage containers.	The maximum scenario includes underground garbage containers planned to be deployed.
5	The minimum scenario for this sensor type takes into account roads with an inclination where slipperiness poses an extra risk for road users, specifically highway exits, bridges and tunnels.	The maximum scenario takes into account bicycle lanes as well.
6	Based on the Hotspot locations mentioned before.	A margin of 100%.
7	Based on the number of traffic control installations (250), measuring traffic coming and going in every direction requires 8 sensors per traffic control installation.	The maximum scenario includes bicycle lanes as well
8	Most of the parking garages in the city of The Hague already keep track of incoming and outgoing vehicles and thus can calculate the number of available places without additional sensors. Measuring availability of street parking spaces seems unnecessary because they are usually occupied only by residents of the neighbourhood. Municipality experts have indicated that priority for measuring parking space occupation lies with parking spaces for disabled people. The minimum scenario starts with 66% of the parking spaces for disabled people.	All parking spaces specifically designated for the disabled.
9	The estimate for this sensor type is based on the Hotspot locations. The Scheveningen beach area, due to its size, is expected to require at least three sound level sensors to accurately measure the sound level in the area.	A margin of 50%.
10	This sensor type is expected to be deployed in residential areas to be able to identify locations of frequent speed violations within the city and to verify traffic measures taken to improve the quality of life of residents. A first estimate of suitable locations is 200. Possibly the functions performed by this sensor can be combined with the vehicle detection sensor type, but this has not been further investigated.	A margin of 50%.
11	The minimum scenario takes into account the largest 33% of tunnels and underpasses within the city.	The maximum scenario takes into account all tunnels and underpasses.

3.2.6. Sensor pilots in other municipalities

Similar to the Zichtenburg pilot, sensor pilot projects have been initiated in several municipalities, sometimes still continuing today. Sensor pilots are usually started by local governments in cooperation with equipment manufacturers and universities or other research institutes to explore the possibilities of using sensor technology in the public space and to gain experience with deployment and maintenance. This section compares the results obtained from the study of The Hague municipality with the choices made for sensor types in other sensor pilot projects. Table 3.5 shows the sensor types selected for The Hague municipality next to the sensor types used in Eindhoven [28], Assen [111] and Santander [96].

From this comparison, it can be concluded that most of the sensor types in table 3.1 are selected in multiple sensor pilot projects. It seems that the investigated municipalities did have the same Smart City goals in mind when determining the set of sensor types for their respective sensor pilots. The only exception to this observation is the use of smart electricity meters in Santander [96]. This sensor type is not mentioned in any of the other cities and does not directly serve the municipal organisation as the meters are installed in buildings. A possible explanation is that in The Netherlands, where the three other compared cities belong to, the deployment of smart electricity meters is a responsibility of the national government [85].

The selected sensor types have been related to the Smart City characteristics described in section 2.4.2, as shown in the last column of table 3.5. From this column it can be observed that all sensor types predominantly relate to the characteristics Smart Environment, Smart Mobility, Smart Living or Smart Governance. Apparently, the characteristics Smart Economy and Smart People are not served in a direct sense by means of sensors in the urban public space.

Table 3.5: Comparison between sensor types used in different Smart City pilot projects

Den Haag	Eindhoven	Assen	Santander	Smart City characteristic(s)
Air quality sensor		Particulates sensor	Air quality sensor	Smart Environment Smart Mobility
Air temperature sensor	Air temperature sensor	Air temperature sensor		Smart Environment
Garbage level sensor				Smart Environment Smart Governance
Ground temperature sensor				Smart Environment Smart Mobility
Parking space occupation detector			Parking space occupation detector	Smart Living Smart Mobility
Sound level sensor	Sound level sensor	Sound level sensor	Sound level sensor	Smart Environment Smart Living
Video camera	Video camera	Video camera		Smart Governance Smart Living Smart Mobility
Vehicle detection sensor	Vehicle detection sensor	Vehicle detection sensor		Smart Mobility
Vehicle speed sensor				Smart Mobility
Water level sensor				Smart Environment Smart Mobility
WiFi/Bluetooth detector	WiFi/Bluetooth detector	WiFi/Bluetooth detector		Smart Governance Smart Living Smart Mobility
		Air humidity sensor		Smart Environment
			Ground moisture sensor	Smart Environment
	Rainfall sensor			Smart Environment
			Smart electricity meter	Smart Environment Smart Living
		Wind speed meter		Smart Environment

3.3. Connectivity options

This section describes a selection of telecommunications access technologies that are currently offered to the market. These include both wired and wireless technologies, technologies that can only be used through an operator and technologies that can be used to form local area networks in unlicensed spectrum. After a general description of each technology, section 3.4 discusses the selection criteria and ranking of each technology for the connection of sensors in urban public space.

3.3.1. Network topology

Before examining the available telecommunication technologies in detail, this section considers the possible network topologies available for the connection of sensors. Figure 3.7 shows three network topology scenarios. The scenarios differ in the type of connections that are used and how data is routed towards the destination. In the scenario shown in figure 3.7a, every sensor node (pink) has a direct connection with the telecom network through one of the telecom access nodes (green). All connections in this scenario are therefore managed by a telecom operator and sensor nodes form a star topology around the telecom acecss node. Compared to scenario A, the hybrid scenario B adds the availability to transfer data from one sensor (blue) node through another sensor node (red) that has a direct telecom connection. The sensor node that receives data from other sensor nodes is often called a sink in the sensor network. The capability of sensor nodes to form connections independently of the telecom network is expected to reduce the operational cost of the sensor network.

Finally, scenario c assumes all sensor nodes connect to a sink to transfer their data. In this ad-hoc scenario only sinks can have a direct connection with a telecom access node.
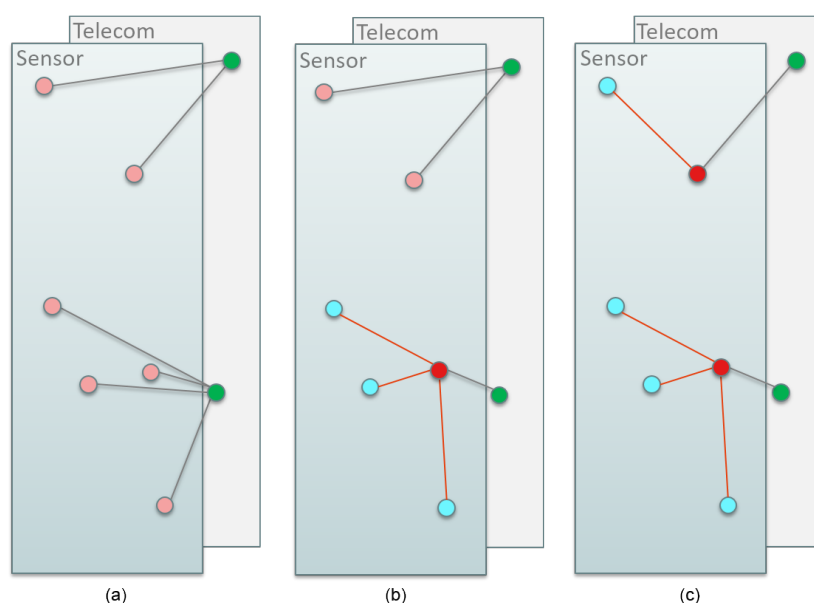
Figure 3.7: Three network topology scenarios to connect sensors to a telecom network:
a: Star topology with direct telecom connections
b: A hybrid telecom ad-hoc scenario
c: A full ad-hoc scenario

In the three scenarios discussed above, two types of connections can be distinguished:

1. Connections between sensor nodes

2. Connections between sensor nodes and telecom nodes

The following subsection discusses technologies capable of providing functions required for one of the mentioned connection types.

3.3.2. Wireless connectivity

Global System for Mobile communication

Global System for Mobile Communication(GSM) is a widely used standard for wireless digital mobile communication, often referred to as 2G. It was originally developed to support two-way mobile voice communication through a circuit-switched architecture. The option of data communication was added to the standard later, first via circuit-switched technology but with the addition of GPRS, GSM also supports packet-switched communication. GSM supports communication in several frequency bands, in The Netherlands primarily the bands GSM900 and GSM1800 are used by the operators. GSM is, at the moment, frequently used as a technology to support M2M communication because it allows for low cost, low bitrate communication.

Universal Mobile Telecommunication System

Universal Mobile Telecommunication System (UMTS) is the successor of GSM and often called 3G. It was standardised by the *Third Generation Partnership Project* (3GPP) with *Release 99* in the year 2000. Later improvements were made in subsequent releases, like the introduction of HSDPA in *Release 5*. It is designed to support both voice and data communication, hence the term *Universal* in the name. It can use the same frequency bands as the GSM network but is often deployed in the 2100 MHz band.

Long Term Evolution

Long Term Evolution (LTE) is a standard based on improvements made by 3GPP to the UMTS standard. It was introduced with the completion of *Release 8* by the 3GPP in 2008. Although not fully meeting the requirements as specified by the ITU, this version of LTE is commonly referred to as 4G. Since *Release 10* in 2011, with the addition of LTE Advanced, LTE can be officially considered a 4G network. LTE does not offer a circuit-switched voice network, instead all traffic is IP based packet-switched. This makes LTE at the moment the cellular technology best suited to transport large amounts of data.

Low Power Wide Area Networks

Low Power Wide Area Networks (LPWANs) form a class of wireless networks specifically designed to provide M2M communication, supporting devices with limited power budget and low bandwidth requirements spread over a large area. Some examples of network technologies belonging to this class are LoRaWAN, SigFox and Narrowband-IoT. Networks in this class mainly target battery powered devices on remote locations that need to be operational for many years without maintenance. One way to achieve such a low power consumption at the device, is to limit the time the device is active to only the time slots that are needed to sent the required data. This way, the device can stay in a state of very low power consumption between transmissions, only to become active when new data needs to be transmitted. The downside of this power saving approach, is that the device is unavailable for network initiated communication for most of the time. This is one of the reasons that this type of networking is typically found in use cases where most of the data is transmitted from the device towards the network, for example in sensor networks.

Some of the LPWAN networks, like LoRaWAN and SigFox, make use of unlicensed parts of the frequency spectrum for the transmission of data. This has the advantage that network development is cost-efficient because no license fees are required from regulatory agencies and it allows for local network initiatives (in the case of LoRaWAN [100]). The downside of this unlicensed frequency spectrum approach is that end devices are limited by regulation in the amount of time they are allowed to transmit [2]. In the European Union, using the 868 MHz ISM band, this allowed duty-cycle consist of a maximum time-on-air of 1% of an hour per sub-band. Depending on the amount of data to be sent in a message and the used spreading factor for transmission, the time between subsequent messages can be anywhere between a few seconds and a couple of minutes. This could limit the applicability of LoRaWAN for some real time applications.

Bluetooth

Bluetooth is a short-range wireless technology for communication between devices, initially developed as a replacement for short cables to peripherals and mobile phones. Created by Ericsson in 1994, the work was later transferred to the specially created *Bluetooth Special Interest Group* (SIG) which consist of companies from the telecommunications, electronics and networking industry [92]. Bluetooth uses the license-free 2.4 GHz band and deploys the frequency-hopping spread spectrum technique to minimize interference and power levels.

Bluetooth has different successive versions, starting with Bluetooth 1.0 up to the newest Bluetooth 5 that is expected to be introduced in devices in 2017 and has been claimed to be more suitable for IoT devices [91]. Bluetooth 4.0 introduced a feature called Bluetooth Low Energy, which is also available in the new Bluetooth 5. This feature allows devices to reduce the power consumption, at the expense of a reduced throughput but with comparable transmit range, and is particularly favorable for IoT devices.

IEEE 802.11
IEEE 802.11 is a collection of standards for wireless local area networks that together are better known by the public as *Wi-Fi*. The 802.11 collection is comprehensive as it consists of dozens of amendments to the main standard, each with their own identification in the form IEEE 802.11*xx*. The first 802.11 standard was released in 1997 and amendments have been published continuously since then. 802.11 could be seen as a form of *wireless Ethernet*, as it performs roughly the same functionality, although a lot of complexity has been added to be able to handle the wireless channel correctly [34]. 802.11 networks operate mostly in the license-free ISM bands 2.4GHz and 5GHz, although recent changes to the standard allow operation even in the 60 GHz band. 802.11 serves a broad range of use cases, it is being used both in home and office scenarios and in public hotspots or large campus networks to provide users with connectivity.

IEEE 802.11 defines two modes of operation, infrastructure and ad-hoc. The most common used mode is the infrastructure mode, in which a central Access Point provides connectivity to the wireless clients within its coverage area [21], and clients can only communicate through the Access Point. The ad-hoc mode allows clients to communicate with each other without a central Access Point, provided they are within communicating range.

ZigBee
Zigbee is a specification for wireless data communication, build on top of the IEEE 802.15.4 PHY and MAC layers [10]. It is developed and maintained by the ZigBee Alliance and originates from 1998. ZigBee is supposed to be a simple, low cost protocol targeting low data rate applications and battery powered devices. ZigBee supports so called mesh-networking, a network topology that allows data to flow in the network because nodes relay data for each other. There is no need for a central node as present in a star network, and nodes can reach any other node connected to the network through (multiple) hops via other nodes. This allows the range of a ZigBee network to be much larger than the range of a single link between an access point and a client.

3.3.3. Wired connectivity

Wired connectivity for Wide Area Networks (WAN) is often realised through one of two physical media, optical fibre, copper cable or a combination of both. Figure 3.8 shows schematically the different types of physical medium used in a connection from the operator network (left) to the end-user (right). The next two sections discuss the two physical media in more detail.

Optical fibre
In cases where large bandwidth requirements apply, optical fibre can be used as a physical layer to provide connectivity to devices. Using optical fibre in the entire chain between provider and customer is often referred to as *Fibre to the X* (FttX), where *X* can be replaced with any destination that is applicable. For example, *Fibre to the Home*, *Fibre to the Office* and even *Fibre to the Device*. Figure 3.8 shows the use of optical fibre from the Optical Distribution Frame (ODF) at the operator to the end-user, indicated by FttH.
Commercial speeds offered to customers in The Netherlands via optical fibre can be as high as 10 Gbit/s symmetrical, although these speeds are rarely seen towards home or office destinations. Typically, commercial connection speeds over optical fibre range between 50 and 500 Mbit/s. The downside of choosing an optical fibre based connection is that its availability strongly depends on geographical location. The amount of homes-passed, the number of homes that are or can be easily connected to a fibre network, has been reported to be 2.527 million in the second quarter of 2016 [29]. Apart from consumer-grade optical fibre connections (FttH) that are mostly depending on large scale roll-outs, Fibre to the Office can be ordered at any location. When an optical fibre connection is not already available at a certain location, high cost of construction must be taken into account.
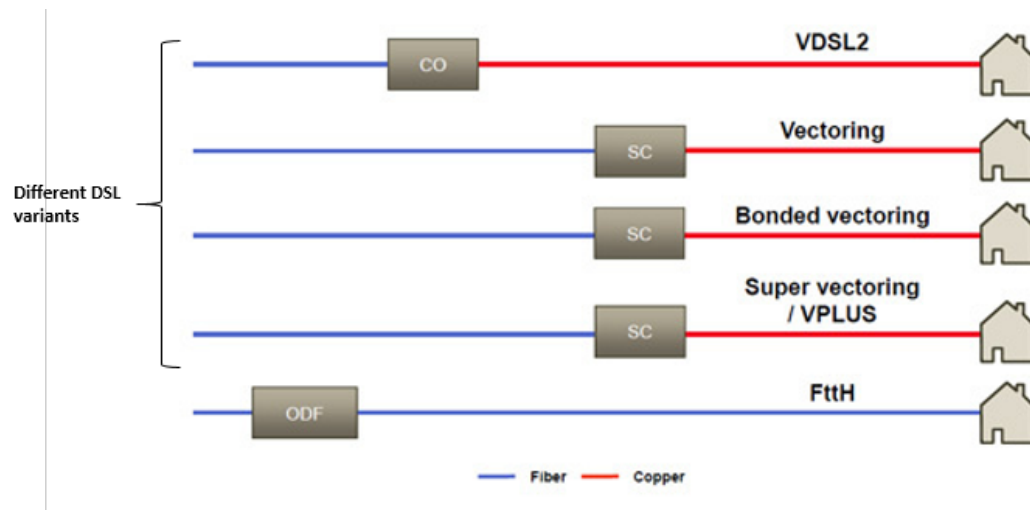
Figure 3.8: DSL and FttH architecture[3]

Copper

Copper networks traditionally used for fixed telephony can nowadays be used to provide broadband data services. This is done by means of a technology called *Digital Subscriber Line* (DSL). DSL comes in many forms, types and variations depending on the local situation and customer needs. Some frequently used types for the consumer market are ADSL (Asynchronous DSL) and VDSL (Very-high-bit-rate DSL), and their successors ADSL2, ADSL2+ and VDSL2. The traditional fixed analogue telephony service still functions while DSL is being used on the copper network, because separate frequency bands are being used for both services.

The copper network owned by KPN has traditionally been deployed into Central Office Service Areas (*Centralegebieden*) that are each served from a central office location. Figure 3.9 shows the relevant Central Office Service Areas around the Zichtenburg area. The distinction between Central Office Service Areas is relevant because the borders of these service areas may cause the distance from the end user to the central office to be larger than expected. Two end users, although physically close to each other, may experience a different data throughput because they are served by different service areas.
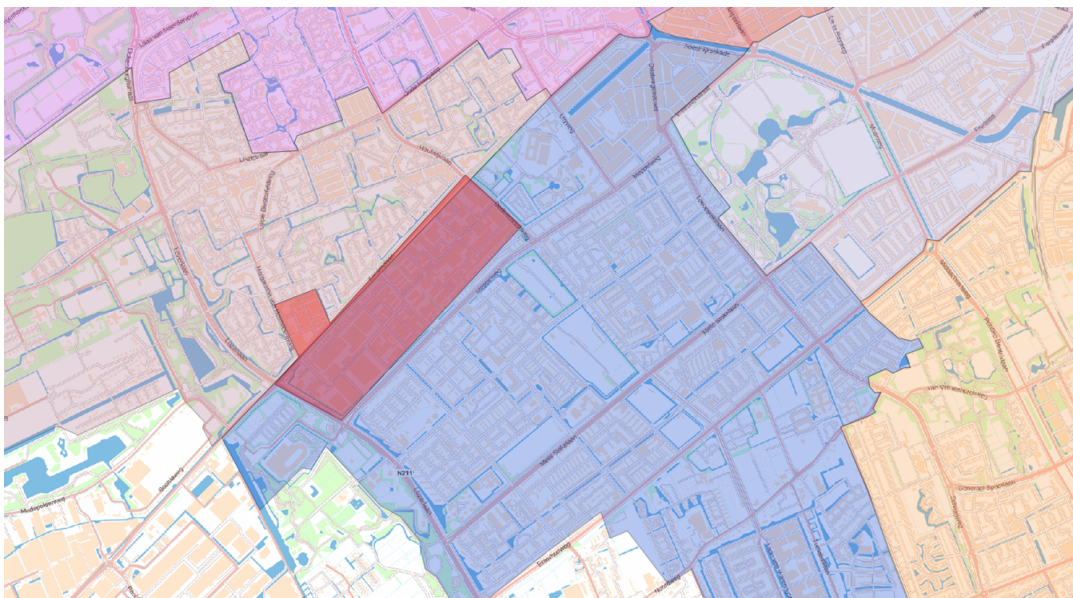
Figure 3.9: KPN Central Office service areas around Zichtenburg

The DSL standards are defined by the ITU-T, and are still being improved to achieve higher bitrates via the

copper network [51]. The increased bitrates on the copper network are possible in part because the length of the copper cable is getting shorter with new DSL architectures. Figure 3.8 illustrates this process. With VDSL2, the distance between the Central Office (CO) and the end-user covered with copper cable is larger than with the newer Vectoring standards that make use of Street Cabinets (SC) connected using optical fibre.

For DSL to work over the existing copper telephony cables, a modem has to be used on the client side of the connection and a DSL Access Multiplexer (DSLAM) needs to be available on the other end. This DSLAM multiplexes the signals from many clients and connects them to a backbone network, usually an IP network as is shown in figure 3.10 [115]. Attainable bit-rates via DSL connections strongly depend on the type of DSL being used, the quality of the copper cables and the distance from the modem to the DSLAM.
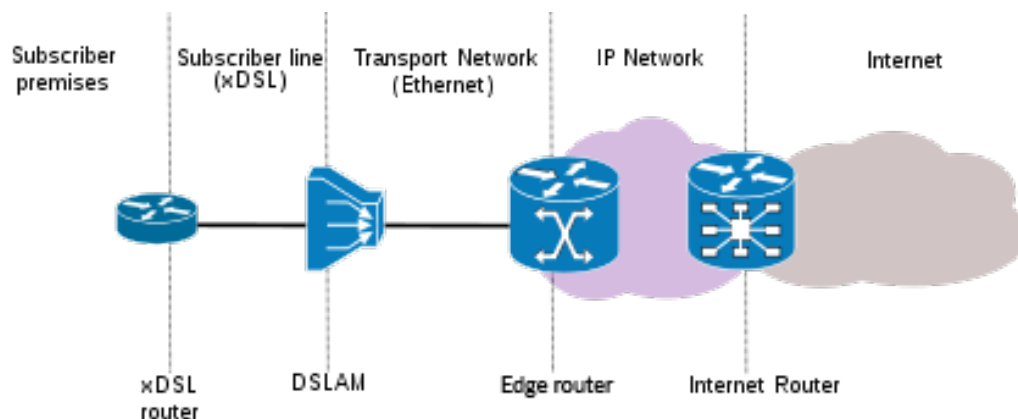
Figure 3.10: DSL path from client to the internet

Summary

Table 3.6 summarizes some key performance indicators of the discussed telecommunication technologies. It is important to notice that the mentioned throughputs and latencies are theoretical values, meaning they are only achievable under ideal circumstances. In practice, however, performance of telecommunication technologies is highly dependent on the user equipment, local (radio) conditions, configurations of the network operator, capacity of the network and many other factors. The values in table 3.6 should therefore be interpreted as an indication of an order of magnitude rather than absolute values.

Section 3.4.1 discusses for some of the technologies the actual attainable performance indicators that have been found for the city of The Hague.

3.4. Connectivity selection

For the telecommunication access technologies described in the previous section, a study has been performed into their suitability to transport sensor data. Technologies can be compared along multiple dimensions. In [83], four dimensions for comparison have been chosen: *Bandwidth*, *Latency*, *Reliability* and *Coverage*. In this thesis, inspired by the previously mentioned dimensions, three criteria have been formulated along which the technologies have been compared.

1. Coverage/Availability; The selected technology should be available in the area where the sensors are going to be placed or should provide sufficient coverage in the area in case of a wireless technology. Local area technologies that do not need a backhaul infrastructure to function, should be able to cover the area given the amount of sensors that are required.

2. Throughput; The selected technology should be able to provide at least the required throughput for one of the sensor types given in section 3.2.

Table 3.6: Summary showing theoretical characteristics of different access technologies

Technology/ Protocol	Standardised by	Max. Throughput (Mbit/s)		Min. Latency (ms)	Max. Range (m)
		Downlink	Uplink		
ZigBee	ZigBee Alliance	0.250	0.250	5-10	10-100
Wi-Fi	IEEE	1300 (ac)	1300 (ac)	1-10	50-250
Bluetooth	Bluetooth SIG	1-3	1-3	100	1-100
LoRa	LoRa Alliance	- [1]	-	4.000-120.000	5.000-15.000
SigFox	SigFox	100 bit/s			10.000-50.000
Narrowband IoT	3GPP				
GPRS	3GPP	0.020-0.085		600-700	1.000-20.000
EDGE	3GPP	0.1-0.25		20-50	1.000-20.000
UMTS/HSDPA	3GPP	300	30		1.000-20.000
LTE(-A)	3GPP	450	150	5-10	1.000-20.000
LTE-MTC	3GPP	1	1		1.000-20.000
ADSL2+	ITU-T	20	1	10-70	2000
VDSL2	ITU-T	20	5	10-70	1500
VVDSL	ITU-T	50	10	10-70	1500
BVDSL2	ITU-T	100	20	10-70	1500
BVVDSL2	ITU-T	200	50	10-70	1500
Optical fibre		1.000[2]	1.000	1-10	∞

3. Expected future availability; The selected technology should be able to provide connectivity for at least the expected life span of the sensor. It is assumed that this period of time should be at least 5 years from now.

Although frequently considered in sensor network research, power consumption relating to the described technologies is not taken into account for the selection in this thesis. The reason behind this lies in the expected deployment of sensors within (existing) street furniture, as discussed in section 2.3.3. Exploiting the existing power infrastructure already in place for the powering of items of street furniture eliminates the need for battery powered sensors and thus the power consumption criterion in the connectivity selection.

3.4.1. Telecom access type characteristics

This section elaborates on the performance of the telecommunication technologies discussed in the previous section.

Wired technologies
Regarding the first criterion, availability of the technology, all the discussed technologies comply for the entire city of The Hague. Although the actual deployment of optical fibre is minimal within the city, deployment of new fibre connections to sensor locations is possible at considerable expense. For the various DSL types in table 3.6 holds that the types ADSL2+ and VDSL2 are available within the entire city. The pair-bonded and

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[1] LoRa transfers data per message. Currently, KPN supports a payload of 50 bytes per LoRa message. The number of uplink messages is limited to 700 per day, leading to an average uplink throughput of 0,4 Byte/s if all messages are used.
[2] Commercially limited to 1 Gbit/s. Theoretical throughputs can be higher.

vectored versions of these DSL types have a more limited availability in the city of The Hague.

For the second criterion of throughput, the actual attainable throughputs has been determined at a sample of 30 sets of coordinates within the city of The Hague. The sample covers all area types mentioned in section 2.3.2. Because KPN network administration does not keep track of geographical coordinates, 50 addresses within 100 meter of a set of coordinates have been taken to represent the actual attainable throughput at this specific set of coordinates. The resulting 1500 data points have been analysed and the results are shown in table 3.7. As discussed in section 3.3, DSL throughput is strongly related to the distance between the end-user and the DSLAM. To further investigate this effect, KPN has provided data originating from a theoretical (validated) model indicating the available throughput compared to the distance to the DSLAM. Results for distances between 0 and 7000 meter are shown in figures 3.12 and 3.13 for downlink and uplink throughputs respectively. For both downlink and uplink, throughputs at short distance (below 50 meter) correspond to the maximum throughputs found in table 3.7. When the distance increases, throughputs rapidly decline up to 2000 meter where VDSL2 and VVDSL2 are no longer functional. ADSL2+, although providing limited throughput in general, is able to retain its functioning over longer distances.

To determine which DSL types will be useful for the connection of sensors in the urban public space of the city of The Hague, figure 3.11 has been created.

(a) Distance from lamp posts to fixed access points in The Hague

(b) Distance from VRI to fixed access points in The Hague
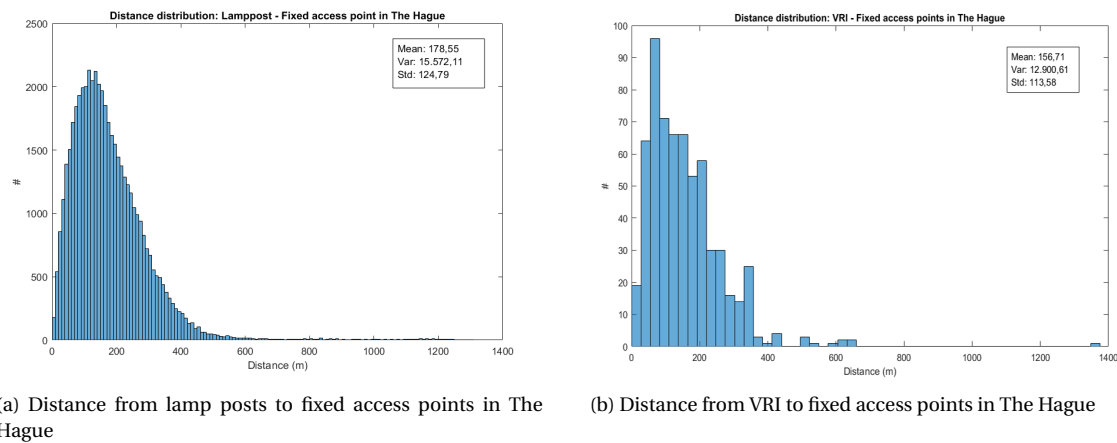
Figure 3.11: Distance statistics of lamppost and Traffic Control Installations to fixed access points in the city of The Hague

Figure 3.11a shows the distribution of the distances between all lampposts in the city of The Hague and their nearest telecommunication access node supporting a fixed access technology. On average, this distance is $178,55$ meter, and the maximum distance that occurs is 1304 meter. Figure 3.11b shows the same distribution for traffic control installations, where the average distance turns out to be $156,71$ meter and the maximum occurring distance 1348 meter.

Relating the found distance distribution to the performance of the discussed DSL variants, it is observed that VDSL2 and VVDSL outperform ADSL2+ in terms of throughput in the distance range of interest for the connection of street furniture. Above 2000 meter, VDSL2 and VVDSL2 are no longer functional, but connections of this length do not appear within the city of The Hague.
The third criterion of expected future availability is hard to assess in absolute terms. Looking at the strategy as described in [61], it seems that focus is on expanding VDSL and optical fibre coverage in the Netherlands. No mention of ADSL is made, from which it can be concluded that all ADSL connections are to be upgraded to VDSL or optical fibre in the future. This is confirmed by examining the analysis in [83] about the future of fixed access networks and the statement in the KPN Technology Book:

> *In the very long run KPN expects that all buildings and houses will be connected with fiber.* [46]

From the analysis discussed above, it is concluded that the wired technologies VDSL2, VVDSL2 and their pair-bonded versions, as well as optical fibre, can be used for the connection of sensor types within the city of The Hague.
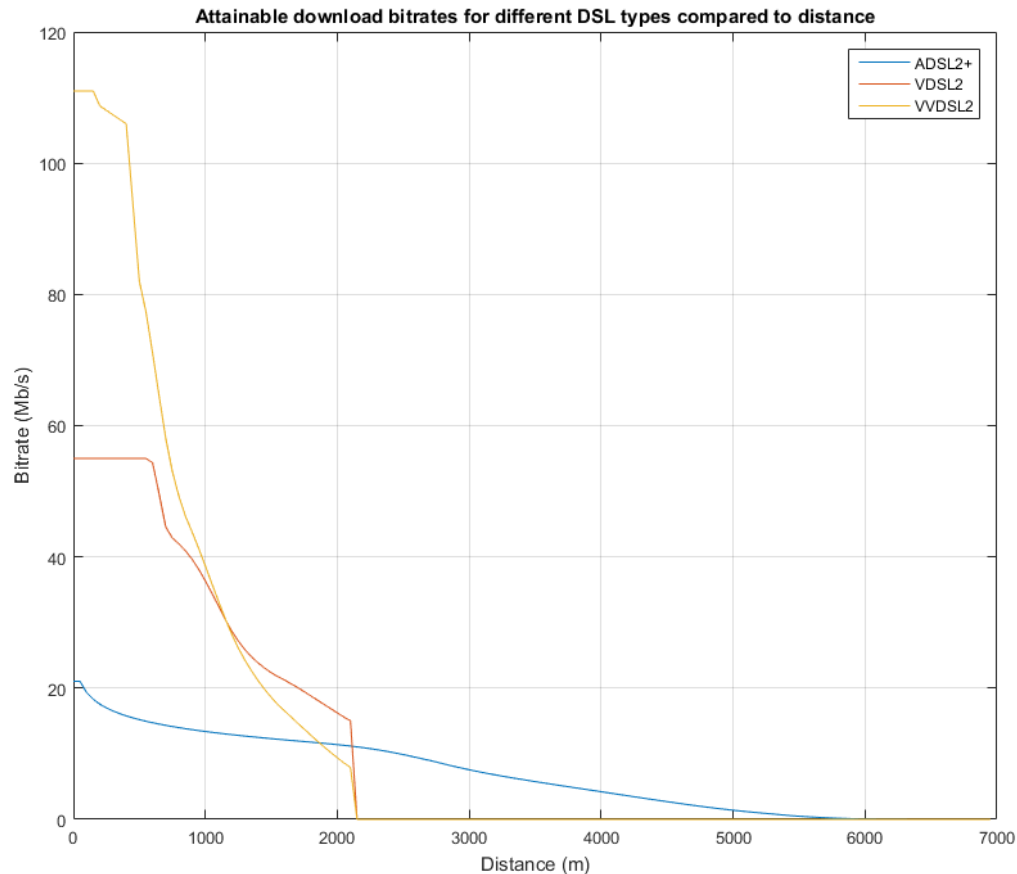
Figure 3.12: Downlink throughputs of different DSL types compared to distance to street cabinet

Wireless technologies

When discussing the wireless technologies a distinction has to be made between Wide Area Network (WAN) technologies and Local Area Network (LAN) technologies. In this thesis, Wide Area Network technologies are those technologies that require an operator to be used and that have the ability to cover a large area. Examples include the described cellular technologies and the LPWANs. Local Area Network technologies can be deployed by anyone, including individuals or organisations not specialised in telecommunications and usually have a limited coverage area. Both types of wireless technologies can be used for the connection of sensors, although the specific use scenarios depend on the network topologies discussed in section 3.3.1. For the remainder of this section, it is assumed that the WAN technologies can be used for connections between sensor nodes and telecom nodes and that LAN technologies can be used for connections between sensor nodes.

Starting with the WAN technologies, the first selection criterion has been investigated using the coverage maps shown in figure 3.14. From these maps it is concluded that coverage of the selected technologies is available for the entire area of the city of The Hague, except for parts of the beach area near the dunes.

Regarding throughput, table 3.8 shows attainable upload throughput as measured by [76] using mobile phones distributed in The Netherlands in 2016. All technologies in this table are able to serve some of the selected sensor types in section 3.2, so from throughput perspective all technologies are suitable for sensor connectivity.

No concrete plans exist for the phase-out of any of the discussed technologies within the mentioned 10 year time period. However, with the development of 5G technology it is expected that not all three generations of
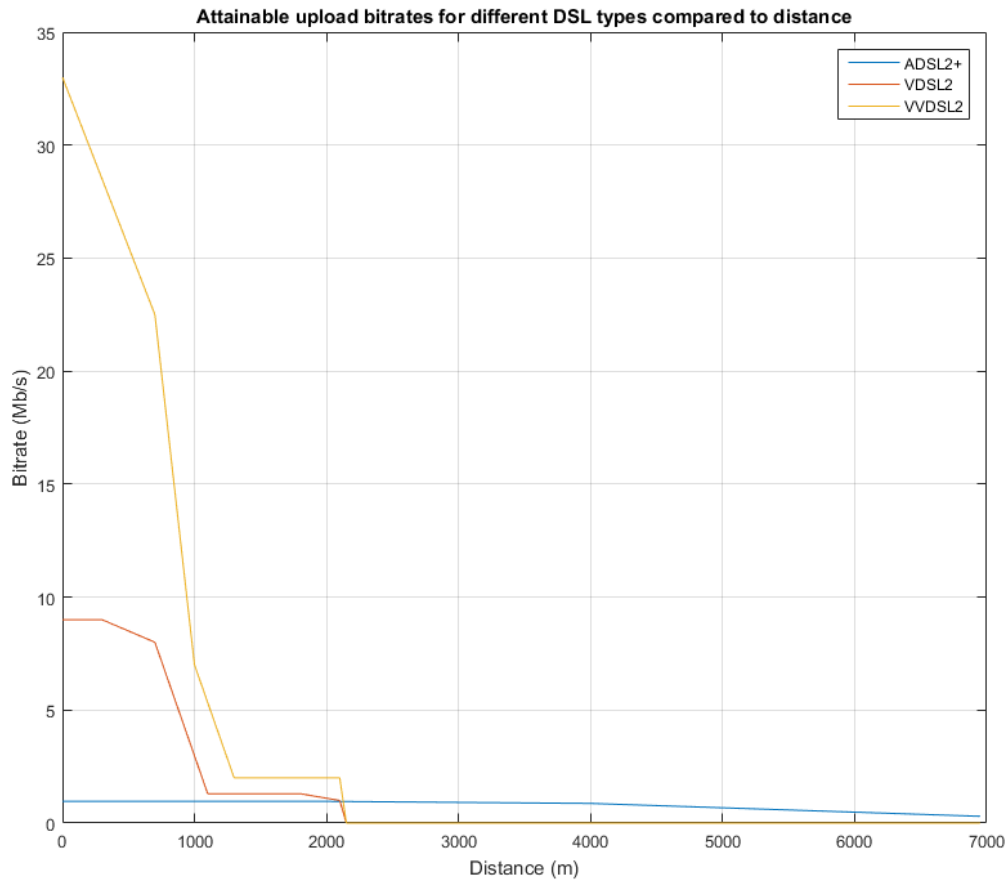
Figure 3.13: Uplink throughputs of different DSL types compared to distance to street cabinet

network technology remain active. For this reason, and the fact that 5G is not yet available, LTE is regarded as the most future proof cellular network technology.

The wireless local area networks, intended to serve as connection between sensor nodes (type 1 in section 3.3.1), all fit the three selection criteria presented. However, ZigBee has a history of connecting sensors in industrial settings [62] and allows for the creation of local mesh networks. For this reason ZigBee has been selected to be included in sensor connectivity simulations in chapter 4.

Table 3.7: Summary of fixed network technology performance in The Hague

Technology	Max. download (Mbit/s)	Avg. download (Mbit/s)	Max. upload (Mbit/s)	Avg. upload (Mb/s)
ADSL2+	22	11,28	0,96	0,94
VDSL2	55	43,02	13	8,39
BVDSL2	110	94,43	26	20,75
VVDSL2	110	102,10	32	28,04
BVVDSL2	220	204,47	64	57,36
Fibre optic	1000		1.000	

Table 3.8: Summary of mobile network performance statistics and attainable bitrates

Category	Technology	Measurements	Avg. upload (kb/s)	St. dev. (kb/s)	Avg. latency (ms)	St. dev. latency (ms)
Cat6	GSM	305	101,87	51,39	282,47	252,98
Cat6	UMTS	10.202	936,97	572,93	75,37	76,15
Cat6	LTE	87.163	18.003,64	13.135,29	36,54	19,92
Cat7	UMTS	15	962,60	515,30	60,60	22,09
Cat7	LTE	201	21.685,10	14.200,73	34	20,71
Cat9	UMTS	50	916,12	530,91	81,36	61,29
Cat9	LTE	1.172	20.810,90	15.083,20	30,78	12,65

3.5. Conclusions

The different sensor types discussed in this chapter that are expected to be useful for The Hague municipality differ in measurement principle, produced amount of data and purpose. Some of the sensor types that are expected to be useful in a future Smart City are to a certain extend already deployed, especially contributing to the Smart City characteristic 'Smart Mobility'. As information can often be obtained through several sensor types, using and combining data from already deployed sensor types for additional purposes likely is a cost attractive way to contribute to the Smart City goals. Nevertheless, there are still some Smart City applications that require sensor types that are rarely seen today and could prove beneficial for the city and its inhabitants. The 11 sensor types identified in this research are

1. Air quality sensor
2. Air temperature sensor
3. Garbage level sensor
4. Ground temperature sensor
5. Parking space occupation sensor
6. Sound level sensor
7. Vehicle detection sensor
8. Vehicle speed sensor
9. Video camera
10. Water level sensor
11. Wi-Fi/Bluetooth sensor

All sensor types predominantly relate to the characteristics Smart Environment, Smart Mobility, Smart Living or Smart Governance. The characteristics Smart Economy and Smart People are not served in a direct sense by means of sensors in the urban public space.

Multiple telecommunication technologies exist that could be used for the connection of sensors to an existing telecommunication network or for the creation of a new sensor network. Both wired and wireless technologies have been discussed in this chapter, each with their own advantages and disadvantages. Considering the
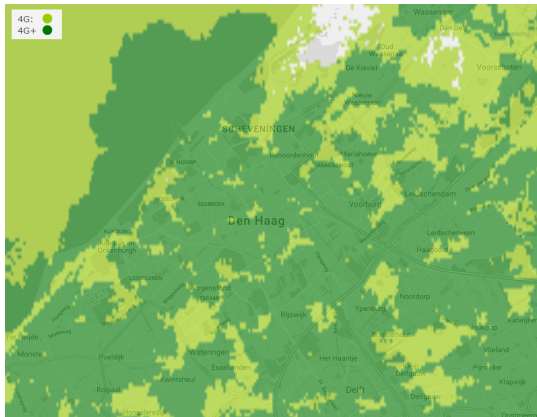
(a) KPN 4G coverage in The Hague [59]
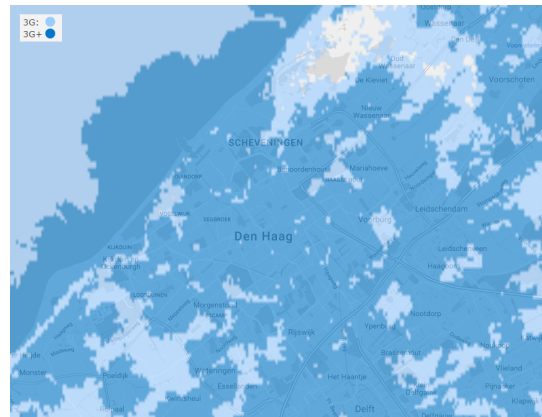
(b) KPN 3G coverage in The Hague [59]
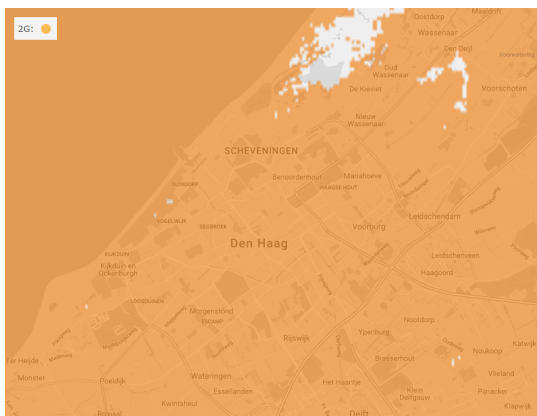
(c) KPN 2G coverage in The Hague [59]
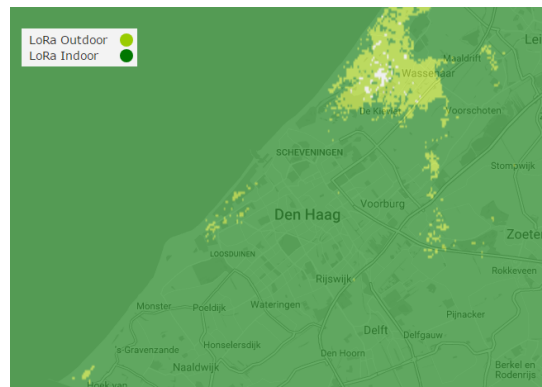
(d) KPN LoRaWAN coverage in The Hague [60]

Figure 3.14: Several coverage maps of Wide Area Network technologies in the city of The Hague

variety of sensors selected for the specific situation of The Hague, the technologies found most promising are

- ZigBee; Only used to provide sensor-to-sensor connections or sensor-to-sink connections

- LoRaWAN

- LTE

- DSL; More specifically the variants VDSL2, VVDSL2 and their pair-bonding versions. The variation that supports the highest throughput at a certain location will be selected

- Optical Fibre

In the next chapter, these technologies will be used to optimise the connectivity of to be deployed sensors in The Hague.

4

Cost optimisation model

This chapter discusses the proposed model that has been developed to address and answer the third research question:

> Given an amount of sensors of different types and requirements, what is the cost-optimal way of connecting them using existing telecommunication access technologies?

The chapter starts with a general overview of the components and tasks, the used tools and data sources and leads to the results presented in chapter 5.

4.1. Model overview

In this thesis, the problem of finding the appropriate connections between installed sensors and telecom nodes at minimum cost is modelled as an interdependent network problem. More specifically, the problem can be defined as a link allocation problem between nodes in two separate networks under constraints imposed by the physical world. The two interdependent networks in this case are the sensor network and the telecom network. These separate networks are depicted in figure 2.4, where solid lines between nodes indicate connections between nodes within a single network and dotted lines indicate connections between both networks.

4.1.1. The sensor network layer

The top layer in the interdependent network model is the sensor layer. The sensor layer consists of sensor nodes, belonging to one of the sensor types selected in chapter 3. A sensor node should be attached to an item of street furniture to determine its geographical position within the city. Each sensor node can only be attached to one item of street furniture, securing its position in space using the Rijksdriehoek-coordinate system (see appendix D for a description of this coordinate system).

A sensor node automatically inherits properties associated to the sensor type it belongs to. For example, a sensor type can be modelled as measuring a certain quantity at a certain measuring frequency, which will propagate to all sensors belonging to that type. This implies that every sensor of a certain type is identical with respect to the properties defined by the sensor type.

Furthermore, a sensor node has properties that are specific for that sensor only. It is possible for a sensor node to become a sink in the sensor network, meaning other sensor nodes can set up ad-hoc connections in order to relay data through this node. This is an individual property of a sensor node and is not determined by sensor type nor location.

49
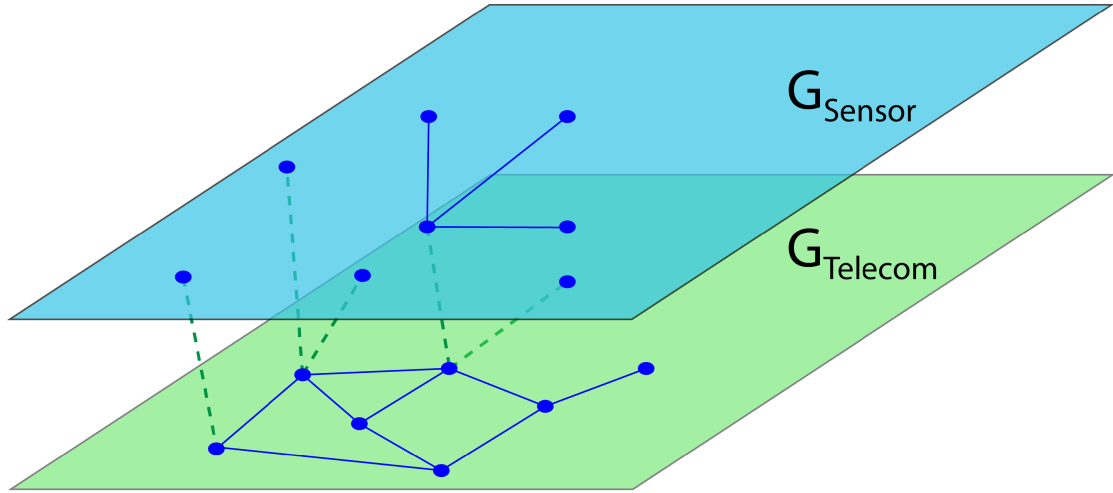
Figure 4.1: Interdependent network model consisting of two networks

4.1.2. The telecom network layer

The second layer is called the telecom layer and consists of telecom access nodes. For sake of simplicity, the connections between these access nodes and their backhaul nodes are not considered in the model. The function of telecom access nodes is to provide connectivity to nodes in the sensor network.

Telecom nodes in the model support certain connection types, discussed in chapter 3, determined by their installed equipment. For example, fixed telecom nodes can support VDSL, VVDSL or optical fibre connections based on the installed DSLAM and configuration. Furthermore, telecom nodes have a geographical location in RD-coordinates.

4.1.3. Dependency links

Connections can be made between sensor nodes and between sensor and telecom nodes. A dependency link is defined as being a connection between a sensor node and a telecom node. Dependency links are expressed as zero or one entries in a dependency matrix B. When N sensor nodes have to be connected to M telecom nodes, the B matrix is of size $N \times M$. A zero entry meaning there is no connection between the specific sensor node and access node, one meaning there is a connection.

The dependency matrix is determined by first assigning weights to all possible dependency links in a weight matrix W. Link weights in the model are based on a combination of technical and financial considerations. First, the technical capabilities of the connection are taken into account by comparing the requirements from each sensor type with the capabilities of each connection type. When no link is possible between a sensor node and a telecom node, for example because the throughput requirements of the sensor node cannot be fulfilled by the access node, an infinite link weight is assigned to the specific link.

The financial component of link weights relates to the cost price (expressed in euro) needed to operate the specific link under the load imposed by the sensor node. In case of newly constructed infrastructure, when fixed access connections need to be constructed for a specific location, the investment cost are taken into account in the link weight as well. The link with the lowest weight is selected as optimal for this sensor node and marked in the B matrix. The procedure for assigning weights and determining the B matrix is described in algorithm 1.

Algorithm 1 Determining the B matrix

$B = Zeros(N, M)$
$W = Inf(N, M)$

for $i = 1 \in \{1, \ldots, n\}$ **do**
    for $j = 1 \in \{1, \ldots, N_i\}$ **do**
        if S_j *has position* **then**
            $B_j \leftarrow$ *Sensor type maximum throughput*
            $C \leftarrow$ *Connection types capable of providing* B_j
            for $k \in \{1, \ldots, C\}$ **do**
                $T \leftarrow$ *All telecom nodes providing* C_k
                for all $t \in \{1, \ldots, T\}$ **do**
                    $w_{jt} = MONTH\_FEE(C_k) + DATA\_FEE(C_k) * AVG\_DATA\_PROD(S_j) + INV\_COST(C_k, S_j, T_t)/EXPECTED\_LIFETIME(C_k)$
                end for
            end for
        end if
    end for
end for

$B = min(W)$

4.1.4. The role of the public space

The public space with its objects and properties isn't modelled as a separate layer, nevertheless it plays an important role in joining the sensor and telecom layer. Every sensor node in the sensor layer has to be mounted on an existing item of street furniture in the public space to receive a location in Rijksdriehoeks-coordinates, and therefore items of street furniture are included in the model with a specific type and a location.

Besides items of street furniture, other special elements in the public space are taken into account in the model. For example, crossroads are important because multiple traffic streams can use the same road section, increasing the probability of accidents. It is for this reason that measures to control the traffic flow are often employed near crossroads, and these measures often require the use of sensors. Other examples include tunnels, highway exits and bridges.
In the modelling of public space elements, a correction parameter is introduced. This parameter is included to account for the fact that items of street furniture are never directly placed within the administered surface of the public space element, because this would hinder the flow of traffic and reduce the safety of road users. Because items of street furniture are placed at some distance away from the actual surface, a mechanism has to be used to determine which items of street furniture are able to house sensors for a particular public space element and which items are too far away. The correction parameter allows to make this distinction.

Crossroads are, in the cost-optimisation model, modelled as a circle with a pair of centre coordinates and a radius in metres, shown in figure 4.2. The radius of the circle is individually determined and is dependent on the surface of the crossroad in the *Basisregistratie Grootschalige Topografie* (BGT) according to the formula

$$R = \sqrt{\frac{\alpha A}{\pi}}$$

Where

α : Correction parameter
A : Area of the crossroad
R : Radius of the modelled crossroad circle in meters

This effectively means that the radius R is chosen so that the resulting circle equals α times the surface of the crossroad A. The value of α that in the city of The Hague yielded usable results is 1.5. This has been deter-

mined by taking samples from the data set with items of street furniture, applying the modelling scheme and comparing the results with the physical situation. It is possible that different area or road types combined with specific sensor types require a different value of α, but this has not been investigated in further detail.
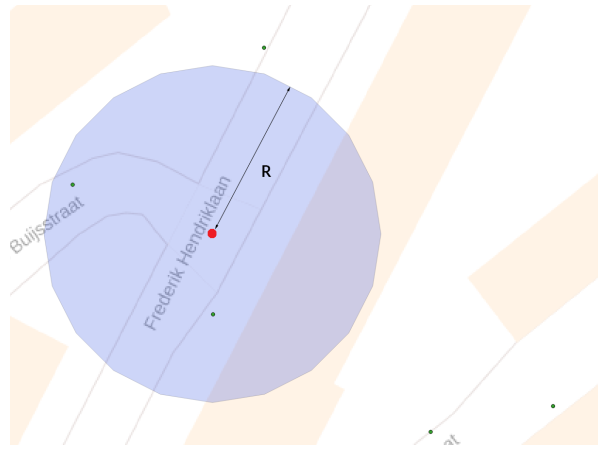
Figure 4.2: Crossroad modelled as a circle with centre coordinates (red dot) and radius R, showing lamp posts as green dots

A similar strategy has been developed for the modelling of roads, although in this case the rectangle has been chosen as the basic form. Figure 4.3 illustrates the modelling strategy. A rectangle (yellow) is chosen to represent the road surface, and a second rectangle (blue) is extended on all four sides by a number of meter according to the formula

$$D = \beta \frac{2A}{P}$$

Where

β : Correction parameter
A : Area of the road
P : Perimeter of the road

The area A of the road is first divided by half the perimeter P of the road in order to obtain approximately the width of the road. Next, the distance D is taken to be β times the width of the road. This approximation is only valid as long as the road is significantly longer than it is wide, but typical roads meet this requirement. For the city of The Hague, a suitable value for β is found to be $\frac{1}{3}$.
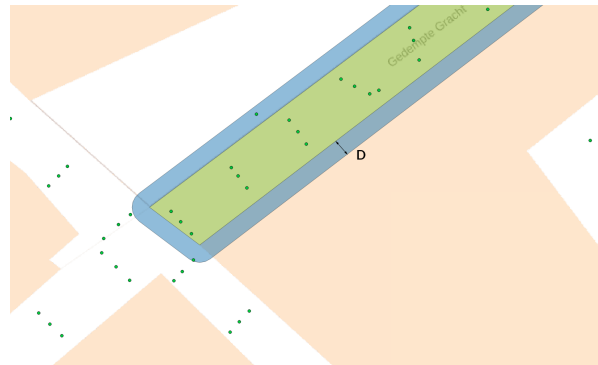
Figure 4.3: Road modelled as a rectangle with extended borders at a distance D, showing lamp posts as green dots

An exception is made for roads that are part of tunnel or overpasses, as the space around these roads is limited by the structure of the tunnel or overpass. In terms of the parameter β, this results in a value of $\beta = 0$ for roads being part of tunnels or overpasses.

Taking into account all items of the public space discussed above, a modelled version of the public space arises as is shown in figure 4.4. This model of the public space is used to determine the items of street furniture matching the placement rules discussed in table 3.4.

Figure 4.4: Part of the street pattern of the city of The Hague modelled using the public space modelling system

4.1.5. Assumptions and simplifications

The cost optimisation model described in the previous section is based on a number of assumptions and simplifications of the real world situation, as discussed with The Hague municipality experts. These assumptions and simplification impact the outcome of the simulations performed using the model, so it is important to be aware of their consequences. This section describes the most important assumptions and simplifications that have been made and identified, and aims to assess their impact on the outcomes where possible.

Assumptions
- Telecommunication nodes are stationary and cannot be moved in space.

- Sensor nodes are stationary and will not move during simulations

- The coverage of wireless access technologies as reported by the coverage maps is assumed to be existing in a place of interest and assumed to be able to provide the reported average throughput, although real physical circumstances can differ in practice

- An item of street furniture that has a connection to the power network is assumed to be able to use this power connection 24 hours per day

Simplifications
- The cost of new fixed telecommunication connections are calculated based on the length of a straight line between the access point and the sensor location, potential deviations from this line due to buildings, waterways or other are not taken into account. It is assumed that these deviations from a straight line will average out when the number of sensor nodes becomes large.

- Each sensor of a particular type of sensors is assumed to behave similarly to the other sensors belonging to the same type, i.e. sensors of the same type are identical and the specific location of a sensor does not affect its behaviour.

- A node in the sensor network can only have one connection to a telecommunication node, possibly combined with multiple sensor connections

- A telecommunications node can have infinitely many connections to sensor nodes, i.e. capacity of the specific telecommunication node with respect to the number of supported connection is assumed to be sufficient

- Transmission of sensor data is assumed to be uniformly distributed in time, i.e. no bursts in the transmission that exceed the average throughput occur in time

4.2. Sensor Planning and Optimisation Tool

A simulation tool has been implemented in MATLAB in order to perform calculations and simulations with the model described in section 4.1. Named *Sensor Planning and Optimisation Tool (SPOT)*, the simulation tool follows a step-wise approach to optimise the cost of sensor connectivity in the public space. Section 4.2.1 discusses the simulation strategy that has been chosen to answer research question 3. Section 4.2.2 provides more details regarding the calculations performed during the simulations.

4.2.1. Simulation strategy

The simulation is divided into four parts, together leading to an answer to research question 3. It is assumed that the final cost of connecting the sensor nodes to a telecommunication network is largely depending on the location of the sensor nodes and the chosen telecommunication access technologies. The parts have been chosen to be able to distinguish between the location aspect of the connectivity cost-optimisation and the telecom access technology aspect. Part A leaves the location aspect out of scope, and assumes a random distribution of sensor nodes over the different area types. The goal of part A is to obtain a basic cost level to compare with subsequent parts.
Part B adds the placement rules given by The Hague municipality to the sensor nodes, to obtain insights into the effect of requiring specific sensor node locations in the cost-optimisation.
Part C takes the result from part B as input and tries to optimise the locations of the sensor nodes within the boundaries given by the placement rules.
Part D takes the calculated sensor node locations from part C as input, and tries to reduce the total link weight by determining appropriate sensor nodes to form a local ad-hoc network.
Table 4.1 gives an overview of each of the steps and the expected outcomes.

4.2.2. Simulation steps

Each of the simulation strategy parts performs a number of steps to come to a final result.

Rule processing
For simulation part B, specific placement rules given by The Hague municipality have to be interpreted and processed by the simulator. For this reason, a standard rule 'template' has been created as can be seen in the entity relationship diagram of the simulator in appendix E. Each sensor type has a placement rule that describes the characteristic public space elements from section 4.1.4 for which this sensor type is important. It also specifies the items of street furniture that the sensor type can be placed on and the amount of sensors to be placed according to the minimum and maximum scenario. The rule processing step determines an initial placing of the sensor nodes based on this rule and an initial item of street furniture to attach the sensor node.

Table 4.1: Applied simulation strategy

Part	Description	Outcome
A	Part A assumes a random distribution of the selected sensor types. Sensors are spread randomly over the area types and the resulting locations are used to calculate the connectivity deployment cost.	Random placing of sensors according to the minimum and maximum scenario and the resulting network cost per area type.
B	Sensors are placed according to the placement rules given by The Hague municipality, bounded by the minimum and maximum scenario.	Placement of sensors according to the placement rules and resulting network cost per area type.
C	Sensor locations are chosen, within the boundaries of the placement rules and the minimum and maximum scenario, to optimise the resulting network cost.	Optimal sensor placement and resulting network cost per area type.
D	A clustering of sensor nodes is performed, to determine suitable locations for (small) local ad-hoc networks. Within each cluster a node is designated to perform the sink function. The resulting network topology and cost are compared to the outcome of part C.	Locations of sensor clusters and possible cost savings due to the use of local ad-hoc networks.

Determining the W matrix

The W matrix contains the link weights assigned to links between sensor nodes and telecom nodes. Determining the link weights is done using algorithm 1 after the rule processing step.

Determining the B matrix

The B matrix is a dependency matrix describing the allocation of links between the sensor network and the telecom network. Individual elements in the B matrix are determined based on the values in the W matrix according to algorithm 1.

Placement optimisation

The rule processing step is responsible for determining the amount of sensor nodes required, and their initial position, but this position is not necessarily the optimal position in terms of telecom cost. This step tries to reduce the total link weight by moving sensor nodes between items of street furniture in the vicinity of the original position resulting from the rule processing. The amount of freedom to move sensor nodes is determined by the modelling of the public space described in section 4.1.4.

Clustering of nodes

For the final part of the simulation strategy, it is necessary to identify clusters of sensor nodes that are geographically close together. For this step, an algorithm is used that clusters nodes together that are within a distance d_{max} of each other. Sensor nodes that have no other sensor nodes within d_{max} are not assigned to a cluster. The process is shown in figure 4.5 with $d_{max} = 50$ meter. Figure 4.5a shows 50 nodes randomly placed in a 500 x 500 grid. In figure 4.5b, nodes that are within $d_{max} = 50$ meter of another node are placed in a cluster together with that node, indicated by a colour. Note that this does not mean that every node within a cluster is within 50 meter of every other node, as a new node only has to be within a distance d_{max} of any single node in the cluster in order to be added. Figure 4.5c shows the centroid of each cluster, i.e. the point in the X,Y grid for which the sum of the distance between the point and every node in the cluster is minimal. The node closest to the centroid is indicated in figure 4.5d.

4.2.3. Software tools

MATLAB

MATLAB is a numerical computing program, as well as a programming language [99]. *MATLAB* performs the required calculations using the input data and parameters, and writes the resulting sensor locations, connec-

(a) Random points in X,Y grid

(b) Initial clustering of nodes within 50 meter of each other

(c) Same clustering showing the centroid of each cluster

(d) Same clustering identifying the node closest to the centroid
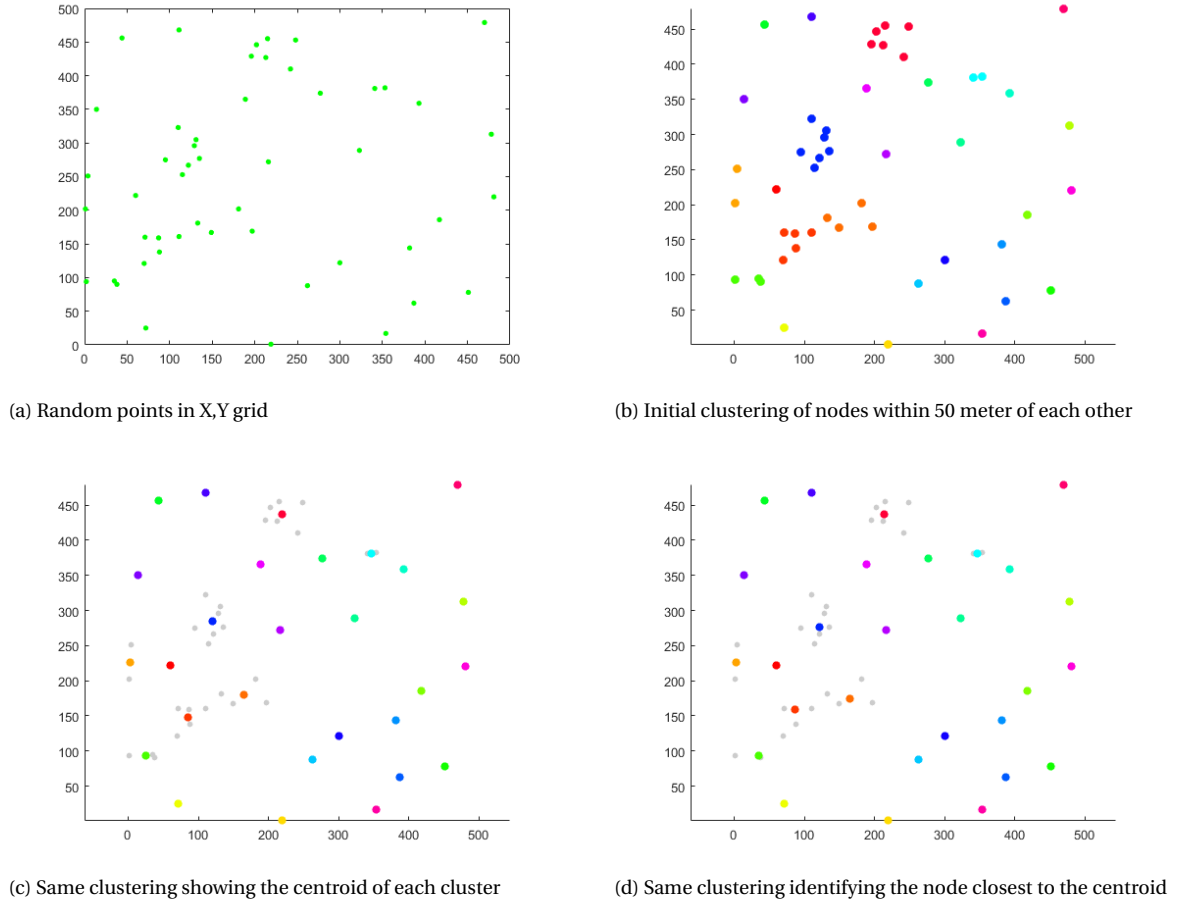
Figure 4.5: Clustering algorithm example

tions and access points to shape files for visualisation and analysis.

QGIS

QGIS is an open-source geographical information system (GIS) [81]. It is capable of plotting geographical data on a map with a large amount of freedom in presentation and configuration. The results calculated by *MATLAB* are processed by *QGIS* to produce maps and images. *QGIS* allows one to combine data from multiple maps or datasets and analyse the results. All maps in this thesis are produced with *QGIS*.

4.3. Data sources

The developed simulation tool relies on data sources supplied by four organisations that together provide information about the state of the public space and the telecommunication network. The two layers in the interdependent network model, being spatially tied to the physical world, require information in order to optimise the location of sensors and to be able to estimate available throughputs at certain locations. This information is provided by data sources that will be discussed in the following sections.

4.3.1. KPN

The telecommunication operator KPN owns a fixed access network consisting of copper and optical fibre connections, as well as mobile cellular networks using technologies discussed in chapter 3.

KANVAS
KANVAS is the network administration system within KPN that keeps track of the fixed copper access network. Originally designed to administer the fixed telephony service, it has been extended to provide information on DSL connections running over the copper network as well. It is responsible for all copper cabling from the central office to the end users. Important information obtained from this system include the number of copper pairs leading to an end user, the available capacity of a copper link and the locations of distribution points in the network.

GEOS-FOW
GEOS-FOW is the current geographical information system (GIS) designed to administer the optical fibre access network of KPN. It has a graphical interface that displays the location of optical fibre cables, as well as the distribution points, on a map.

Access Master
Access Master is currently in a test phase within KPN. It is a web based dashboard combining information from multiple back-end systems that manage the network administration. It is able to show for a given address what the attainable bit-rates are per access technology, including xDSL, FttH/FttO, mobile cellular technologies and even microwave links.

4.3.2. The Hague municipality

The Hague municipality provides multiple data sets as open data on its website [42]. For this research the location and types of street lights, traffic lights and other types of street furniture have been obtained through the open data portal, as well as locations of existing sensor types.

4.3.3. Statistics Netherlands

Statistics Netherlands keeps track of municipal borders, areas and neighbourhoods and their official designation and classification. This data is used make a distinction between area types, as well as calculating the percentage of the total city area belonging to a certain area type.

4.3.4. Cadastre

The Dutch cadastre publishes the *Basisregistratie Grootschalige Topografie* (BGT), as discussed in chapter 2. In the simulations, data from the BGT is used to provide the locations of crossroads, tunnels, bridges and other objects within the public space that are interesting to monitor with sensors. The accuracy of the location of objects in the BGT is prescribed by the national government and, depending on the specific type of object, should fall between 0-2 cm for buildings and more than 10 cm for natural areas [36].

4.4. Conclusions

This chapter presented the layered interdependent network model that was designed and used to contribute to the third research question. The two layers in the model are discussed, as well as the included elements in the public space.

An implementation of this model in MATLAB has been discussed, including simulation steps and used data sources from KPN, The Hague municipality, Statistics Netherlands and the national Dutch government. The next chapter presents the results from the simulations that have been performed using these data sources.

5

Simulation results

This chapter shows the results obtained from simulations with the cost optimisation model from chapter 4. Simulation results involving cost figures of telecommunication access technologies have been replaced by [CONF] at the request of KPN due to these figures being classified as confidential. The structure of this chapter follows the simulation strategy outlined in section 4.2.1, and distinguishes between the minimum and maximum sensor deployment scenarios defined for the city of The Hague.

5.1. Outcomes of simulation parts

5.1.1. Simulation part A

Simulation part A involves the random distribution of the sensor types selected in chapter 3 across the city of The Hague.

Minimum scenario
Table 5.1 shows the resulting distribution of sensor types over the different area types in The Hague. This distribution is expressed both in absolute numbers as well as in a percentage of the total number of sensors. The bottom line in table 5.1 shows the percentage of the total city area that each area type covers in the city of The Hague. From this result it can be observed that the share of sensors in each area type is more or less comparable with the percentage of the total city area that is covered by that area type, as one would expect with a random distribution. The only significant exceptions to this observation are the area types featured by residential terrain, forest and the North Sea. This is likely explained by the relatively large amount of street furniture present in residential areas, and the absence of street furniture in the other two natural area types.

(a) Lamp post distribution per neighbourhood, expressed in lamp posts per m^2

(b) Random sensor distribution for the minimum scenario per neighbourhood, expressed in sensors per m^2

Figure 5.1: Comparison between lamp post density and random sensor distribution

Table 5.1: Simulation part A: amount of sensors per sensor type per area type in The Hague for the minimum scenario

Quantity description	Railway terrain	Road traffic terrain	Residential area	Retail, hotel and catering area	Area for public facilities	Area for social or cultural facilities	Business area	Scrapyard	Cemetery	Building site	Other semi-build	Parks and gardens	Sports terrain	Allotment garden	Single day recreational area	Overnight recreational area	Greenhouse area	Other agricultural area	Forrest	Open dry natural terrain	Recreational waters	Other internal waters	North Sea	Total
Air quality	1	19	140	10	0	5	5	0	1	4	0	6	3	0	0	0	0	1	4	0	0	1	0	200
Air temperature	0	2	18	1	0	1	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	25
Camera	6	95	676	61	10	20	49	1	1	11	0	42	12	1	1	0	0	3	7	1	0	3	0	1000
Garbage level	0	4	270	14	1	2	0	0	0	5	0	3	0	1	0	0	0	0	0	0	0	0	0	300
Ground temperature	5	51	313	30	4	14	36	0	2	6	0	23	10	0	1	0	0	0	3	2	0	0	0	500
Number of people	0	5	24	1	1	0	3	1	0	1	0	4	0	0	0	0	0	0	0	0	0	0	0	40
Number of vehicles	11	223	1235	128	16	48	105	0	5	24	0	118	30	9	8	0	0	11	17	7	0	5	0	2000
Parking occupation	4	39	280	35	3	13	28	0	0	5	0	26	7	0	1	0	0	2	2	2	0	3	0	450
Sound level	0	1	3	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	7
Vehicle speed	1	20	133	15	2	9	7	0	0	2	0	3	5	0	1	0	0	0	1	1	0	0	0	200
Water level	0	5	32	3	0	3	3	0	0	0	0	2	0	0	1	0	0	0	0	0	0	1	0	50
Total	28	464	3124	298	37	115	239	2	9	58	0	229	68	11	13	0	0	17	34	13	0	13	0	4772
Percentage	0,59	9,72	65,47	6,24	0,78	2,41	5,01	0,04	0,19	1,22	-	4,80	1,42	0,23	0,27	-	-	0,36	0,71	0,27	-	0,27	-	100,00
Percentage of city covered by area type	0,85	5,47	35,40	2,84	1,65	2,57	5,97	0,08	0,61	2,12	0,05	6,85	4,36	1,08	0,90	0,41	0,24	1,92	3,93	6,97	0,82	2,10	12,83	100,00

This can be seen as well by comparing figure 5.1a with figure 5.1b, showing the distribution of lamp posts across the city next to the density of placed sensors.

Figure 5.2: Simulation part A: random sensor distribution for the minimum scenario

Following the random placement of sensors according to the minimum scenario, the *W* matrix has been calculated using algorithm 1. The *B* matrix resulting from the *W* matrix led to the connectivity distribution shown in table 5.2.

Table 5.2: Simulation part A: number of connections used per access technology per sensor type for the minimum scenario

n	Name	Optical fibre	(V)VDSL	LTE	LoRaWAN
1	Air quality	0	0	0	200
2	Air temperature	0	0	0	25
3	Camera	0	1.000	0	0
4	Garbage level	0	0	0	300
5	Ground temperature	0	0	0	500
6	Number of people	0	0	0	40
7	Number of vehicles	0	0	0	2000
8	Parking occupation	0	0	0	450
9	Sound level	0	0	0	7
10	Vehicle speed	0	0	0	200
11	Water level	0	0	0	150
	Total	0	1.000	0	3772

However, the resulting connectivity distribution in table 5.2 is strongly depending on the parameters set for the different sensor types. Specifically, measurement frequency and the need for real-time measurements influence the suitability of LoRaWAN for sensor types that produce highly dynamic measurements, e.g. sound level sensors.

For the connectivity distribution in table 5.2, the required operational expenditures (on a monthly basis) and the required capital expenditures have been calculated. This calculation only includes the cost required to operate or deploy the connection, cost related to maintenance, power consumption or sensor hardware is not taken into account. A notable figure in the table is the lack of capital expenditures for the LoRaWAN connections. This is because the LoRaWAN network does not require additional investment to provide connectivity to a device, whereas the fixed DSL network needs to be physically extended.

Table 5.3: Simulation part A: Required operational and capital expenditures per deployed access technology for the minimum scenario

Access technology	Operating expenditures	Capital expenditures
(V)VDSL	[CONF]	[CONF]
LoRaWAN	[CONF]	[CONF]
Total	[CONF]	[CONF]

The sensors shown in figure 5.2 produce a certain amount of data. The distribution of this produced data is shown in figure 5.3 for the minimum scenario, where the city of The Hague has been divided into blocks of 1000 x 1000 meter. Every block indicates the amount of produced data in kbit/s due to the sensors within that block. Comparing this figure with figure 5.1a shows expected similarities, because the sensor types that produce higher amounts of data have been distributed evenly over the city.

Figure 5.3: Simulation part A: minimum scenario aggregate data production in kbit/s due to sensors shown on a grid with a resolution of 1000m x 1000m

Maximum scenario

The results for the maximum scenario are comparable with the minimum scenario, except for the larger to-tal amount of sensors, as can be seen in table 5.5. It is observed that the residential areas comprise an even larger percentage of the total amount of deployed sensors. Table 5.4 shows the required operational and capital expenditures required for the maximum scenario. What is noticed from this table is that, although the total number of sensors has increase with a factor 15565/4772 = 3.26, the total amount of operating ex-penditures has only increased with a factor 17851.90/9244.60 = 1.93. This is due to the fact that the largest increase in sensors is coming from the sensor types garbage level sensor (relatively the largest increase) and vehicle counter (largest absolute increase), which both use LoRaWAN as connection type. A similar pattern is observed for the capital expenditures, which follow the increase in number of deployed cameras.

Table 5.4: Simulation part A: required operational and capital expenditures per deployed access technology for the maximum scenario

Access technology	Operating expenditures	Capital expenditures
(V)VDSL	[CONF]	[CONF]
LoRaWAN	[CONF]	[CONF]
Total	[CONF]	[CONF]

Table 5.5: Simulation part A: Amount of sensors per sensor type per area type in The Hague for the maximum scenario

Quantity description	Railway terrain	Road traffic terrain	Residential area	Retail, hotel and catering area	Area for public facilities	Area for social or cultural facilities	Business area	Scrapyard	Cemetery	Building site	Other semi-build	Parks and gardens	Sports terrain	Allotment garden	Single day recreational area	Overnight recreational area	Greenhouse area	Other agricultural area	Forrest	Open dry natural terrain	Recreational waters	Other internal waters	North Sea	Total
Air quality	4	76	560	40	0	20	20	0	4	16	0	24	12	0	0	0	0	4	16	0	0	4	0	800
Air temperature	0	4	36	2	0	2	4	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	50
Camera	9	142	1014	91	15	30	74	2	1	17	0	63	18	2	1	0	0	5	10	2	0	4	0	1500
Garbage level	0	102	6241	382	23	45	0	0	0	115	0	69	0	23	0	0	0	0	0	0	0	0	0	7000
Ground temperature	10	102	626	60	8	28	72	0	4	12	0	46	20	0	2	0	0	0	6	4	0	0	0	1000
Number of people	0	10	48	2	2	0	6	2	0	2	0	8	0	0	0	0	0	0	0	0	0	0	0	80
Number of vehicles	22	446	2470	256	32	96	210	0	10	48	0	236	60	18	16	0	0	22	34	14	0	10	0	4000
Parking occupation	6	58	419	54	5	21	42	0	0	7	0	39	10	0	1	0	0	3	3	3	0	4	0	675
Sound level	0	2	4	0	0	0	2	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	10
Vehicle speed	2	30	199	22	3	13	11	0	0	3	0	4	7	0	2	0	0	0	2	2	0	0	0	300
Water level	0	15	96	9	0	9	9	0	0	0	0	6	0	0	3	0	0	0	0	0	0	3	0	150
Total	53	987	11713	918	88	264	450	4	19	220	0	498	128	43	25	0	0	34	71	25	0	25	0	15.565
Percentage	0,34	6,34	75,25	5,90	0,57	1,70	2,89	0,03	0,12	1,41	-	3,20	0,82	0,28	0,16	-	-	0,22	0,46	0,16	-	0,16	-	100
Percentage of city covered by area type	0,85	5,47	35,40	2,84	1,65	2,57	5,97	0,08	0,61	2,12	0,05	6,85	4,36	1,08	0,90	0,41	0,24	1,92	3,93	6,97	0,82	2,10	12,83	100,00
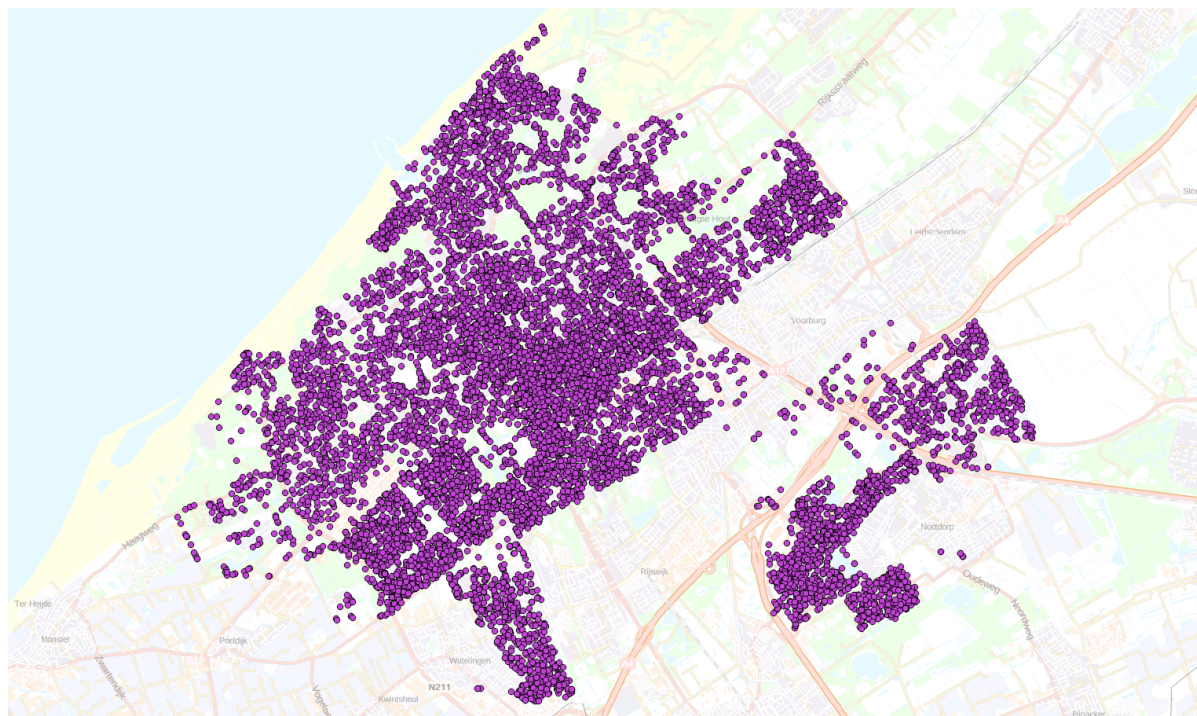
Figure 5.4: Simulation part A: random sensor distribution for the maximum scenario

Table 5.6: Simulation part A: Number of connections used per access technology per sensor type for the maximum scenario

n	Name	Optical fibre	(V)VDSL	LTE	LoRaWAN
1	Air quality	0	0	0	800
2	Air temperature	0	0	0	50
3	Camera	0	1.500	0	0
4	Garbage level	0	0	0	7.000
5	Ground temperature	0	0	0	1.000
6	Number of people	0	0	0	80
7	Number of vehicles	0	0	0	4.000
8	Parking occupation	0	0	0	675
9	Sound level	0	0	0	10
10	Vehicle speed	0	0	0	300
11	Water level	0	0	0	150
	Total	0	1.500	0	14.065
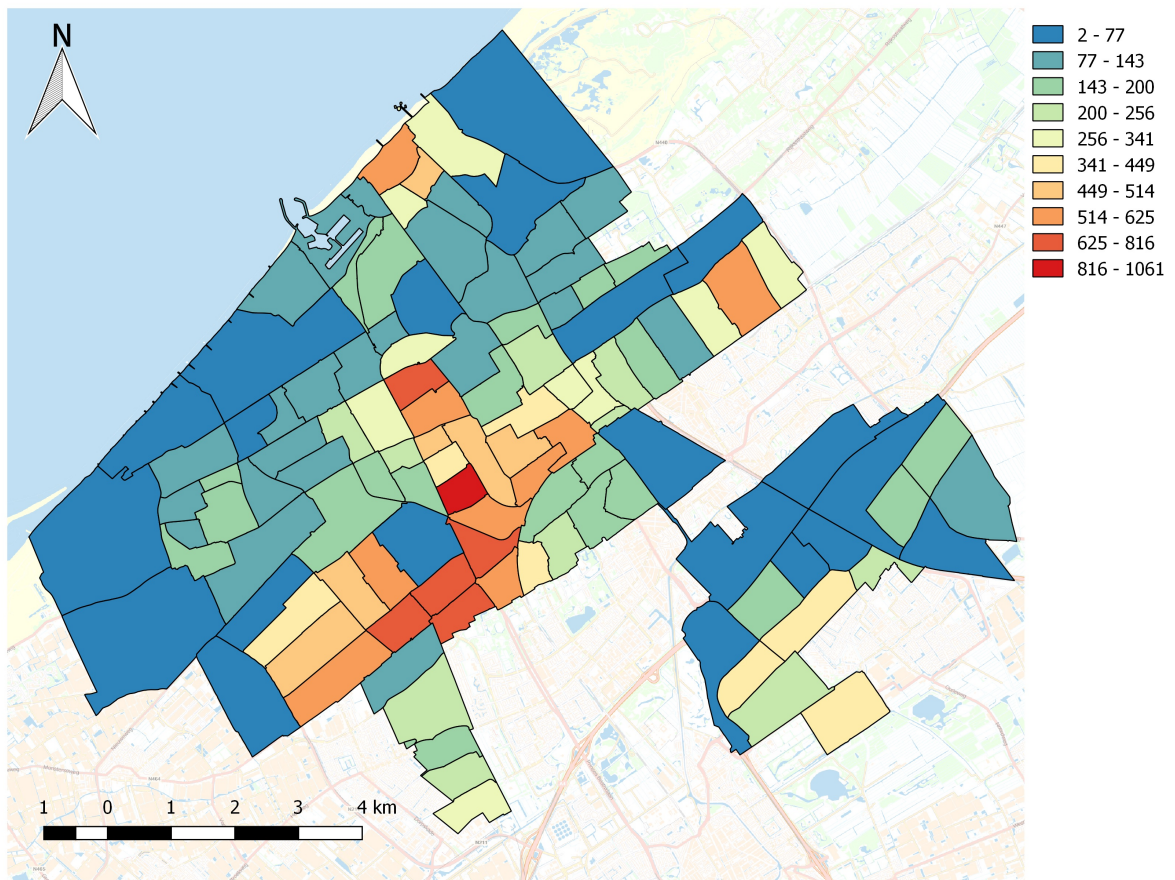
Figure 5.5: Simulation part A: random sensor distribution for the maximum scenario per neighbourhood, expressed in sensors per m^2
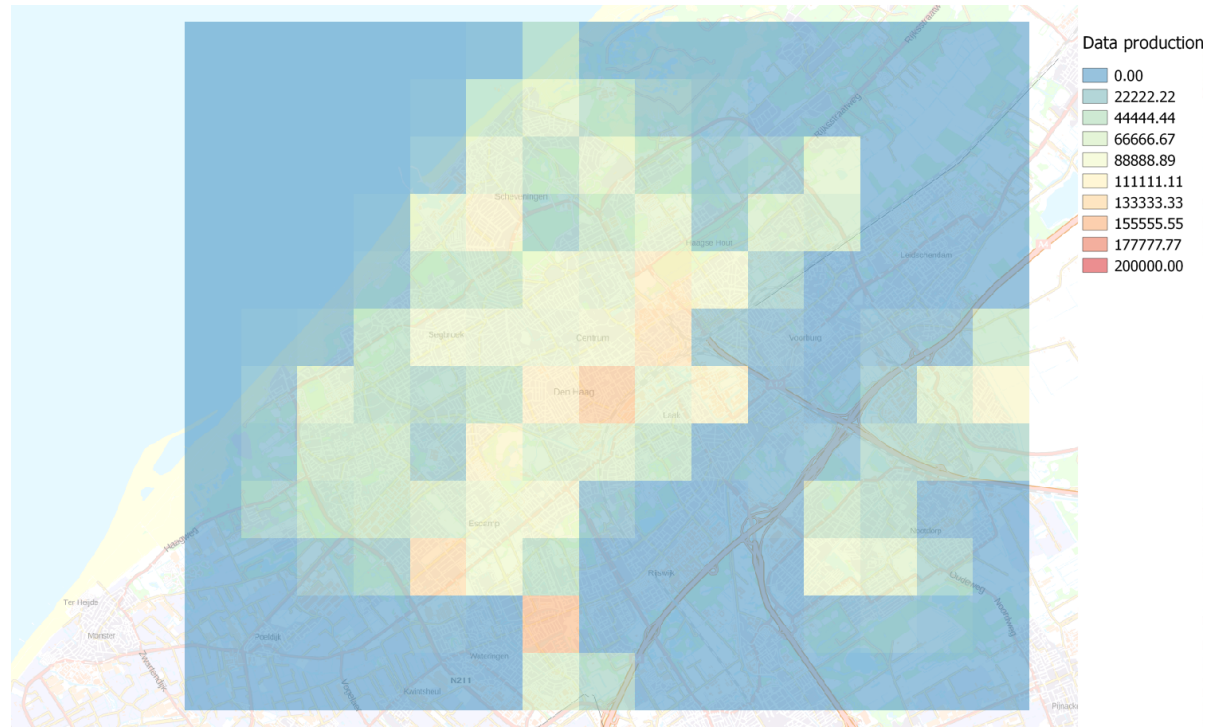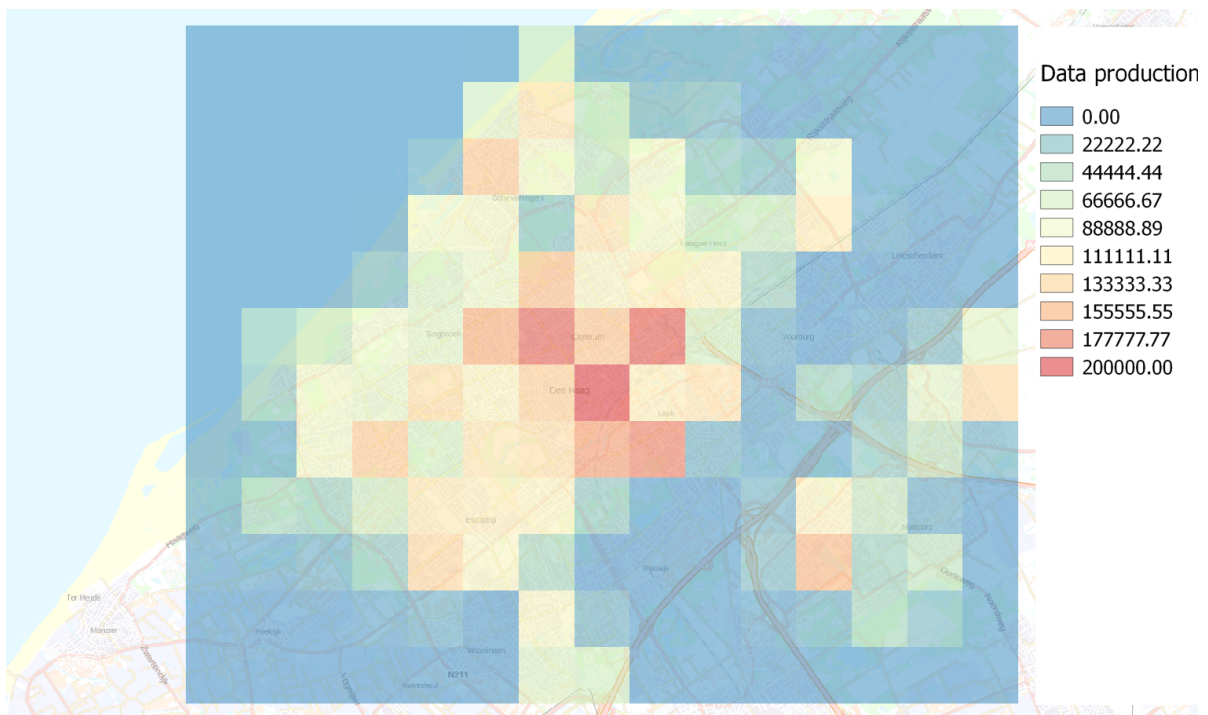
Figure 5.6: Simulation part A: maximum scenario aggregate data production in kbit/s due to sensors shown on a grid with a resolution of 1000m x 1000m

5.1.2. Simulation part B

Simulation part B uses the earlier defined minimum and maximum scenario. Instead of a random placement as done in simulation part A, part B places the sensors according to the placement rules defines in table 3.4. Placing sensors according to these placement rules resembles the real world situation more closely than random placing, and provides insight into the items of street furniture that will fulfil an important role in sensor deployment. Table 5.7 shows for the minimum scenario the most used items of street furniture previously discussed in section 2.3.3. From this table it is observed that the lamp post is by far the most likely candidate for the deployment of sensors in the urban public space.

Table 5.7: Simulation part B: selection of street furniture for the minimum scenario sensor placement rules

Street furniture type	Air quality	Air temperature	Camera	Garbage level	Ground temperature	Number of people	Number of vehicles	Parking occupation	Sound level	Vehicle speed	Water level
Lamp post	197	24	889	-	496	35	1978	445	6	172	50
Traffic control system	2	1	111	-	4	-	22	-	-	28	-
Underground garbage container	-	-	-	300	-	-	-	-	-	-	-
Phone boot	1	-	-	-	-	5	-	-	1	-	-
Parking meter	-	-	-	-	-	-	-	5	-	-	-

Table 5.10 shows the distribution of sensor types over the different area types in the city of The Hague after placing using the placement rules. After applying the placement rules the sensor distribution no longer matches the area type distribution in the city of The Hague. The biggest change is observed for the area type *Road traffic terrain*, which shows an increase in relative amount of sensors from 9.72% in the random simulation to 33,09% when using placing rules. Still the largest part of the sensors is assigned to locations belonging to residential areas, which is understandable given that this area types covers the largest part of the city and includes all *erftoegangswegen* (see section 2.3.2 for the definition of road types).

Table 5.8: Simulation part B: required operational and capital expenditures per deployed access technology

Access technology	Operating expenditures	Capital expenditures
(V)VDSL	[CONF]	[CONF]
LoRaWAN	[CONF]	[CONF]
Total	[CONF]	[CONF]

When examining the cost associated with connecting sensors to a telecom network in the case of placement rules, table 5.8 shows that the operational expenditures are not affected by the placing rules. This makes sense given the distribution of access technologies shown in table 5.9. However, the capital expenditures show a decrease of 28.9%. This can be explained by looking at figure 5.7. The area types that show an increase in the number of sensors requiring a fixed connection also have a large concentration of fixed access points.
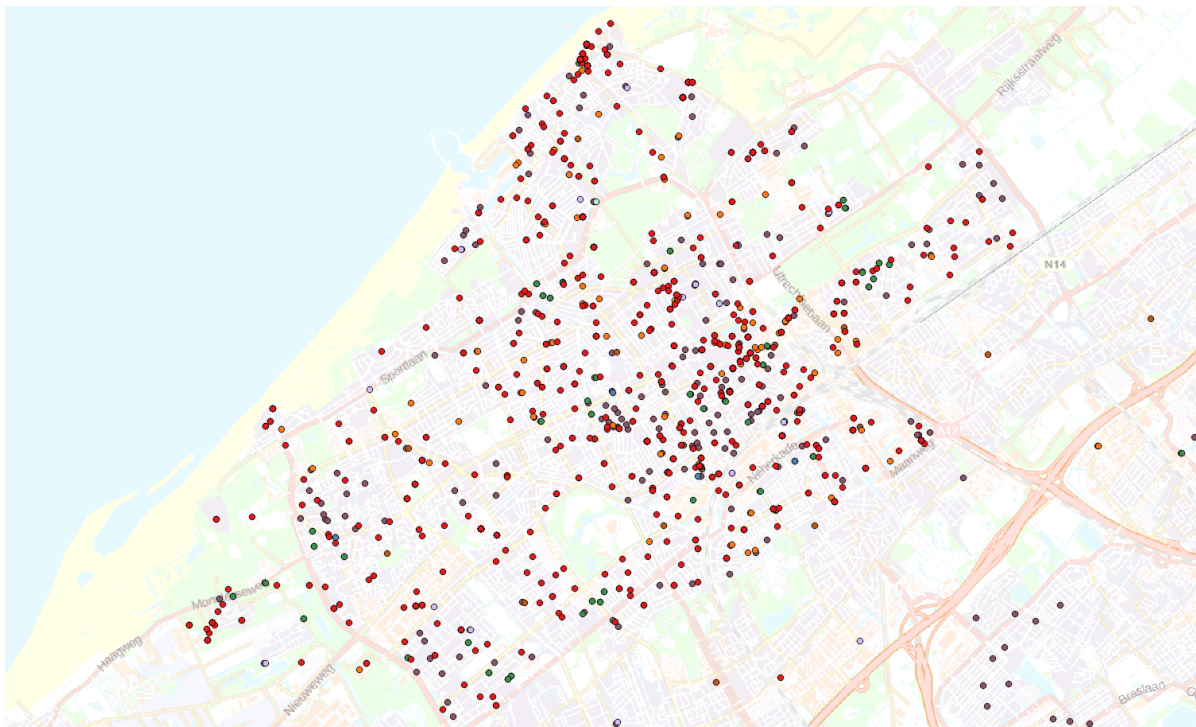
Figure 5.7: Simulation part B: access points to connect to the fixed (DSL) network in the city of The Hague

Table 5.9: Simulation part B: number of connections used per access technology per sensor type for the minimum scenario

n	Name	Optical fibre	(V)VDSL	LTE	LoRaWAN
1	Air quality	0	0	0	200
2	Air temperature	0	0	0	25
3	Camera	0	1.000	0	0
4	Garbage level	0	0	0	300
5	Ground temperature	0	0	0	500
6	Number of people	0	0	0	40
7	Number of vehicles	0	0	0	2000
8	Parking occupation	0	0	0	450
9	Sound level	0	0	0	7
10	Vehicle speed	0	0	0	200
11	Water level	0	0	0	150
	Total	0	1.000	0	3772

Table 5.10: Simulation part B: amount of sensors per sensor type per area type in The Hague for the minimum scenario

Quantity description	Railway terrain	Road traffic terrain	Residential area	Retail, hotel and catering area	Area for public facilities	Area for social or cultural facilities	Business area	Scrapyard	Cemetery	Building site	Other semi-build	Parks and gardens	Sports terrain	Allotment garden	Single day recreational area	Overnight recreational area	Greenhouse area	Other agricultural area	Forrest	Open dry natural terrain	Recreational waters	Other internal waters	North Sea	Total
Air quality	0	105	77	0	0	4	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200
Air temperature	0	7	14	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25
Camera	13	114	649	67	11	33	49	2	6	13	0	41	0	0	2	0	0	0	0	0	0	0	0	1000
Garbage level	0	0	286	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	300
Ground temperature	0	435	43	0	0	3	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500
Number of people	0	9	8	5	1	2	9	0	0	0	0	5	0	0	1	0	0	0	0	0	0	0	0	40
Number of vehicles	0	684	879	61	8	56	189	0	10	0	0	98	0	0	15	0	0	0	0	0	0	0	0	2000
Parking occupation	0	152	153	53	0	19	43	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	450
Sound level	0	3	2	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	7
Vehicle speed	0	36	124	7	0	9	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200
Water level	0	34	12	1	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
Total	13	1579	2247	194	20	143	352	2	16	13	0	175	0	0	18	0	0	0	0	0	0	0	0	4772
Percentage	0,27	33,09	47,09	4,07	0,42	3,00	7,38	0,04	0,34	0,27	-	3,67	-	-	0,38	-	-	-	-	-	-	-	-	100
Percentage of city covered by area type	0,85	5,47	35,40	2,84	1,65	2,57	5,97	0,08	0,61	2,12	0,05	6,85	4,36	1,08	0,90	0,41	0,24	1,92	3,93	6,97	0,82	2,10	12,83	100,00

Figure 5.8: Simulation part B: map showing placement of sensors according to placement rules
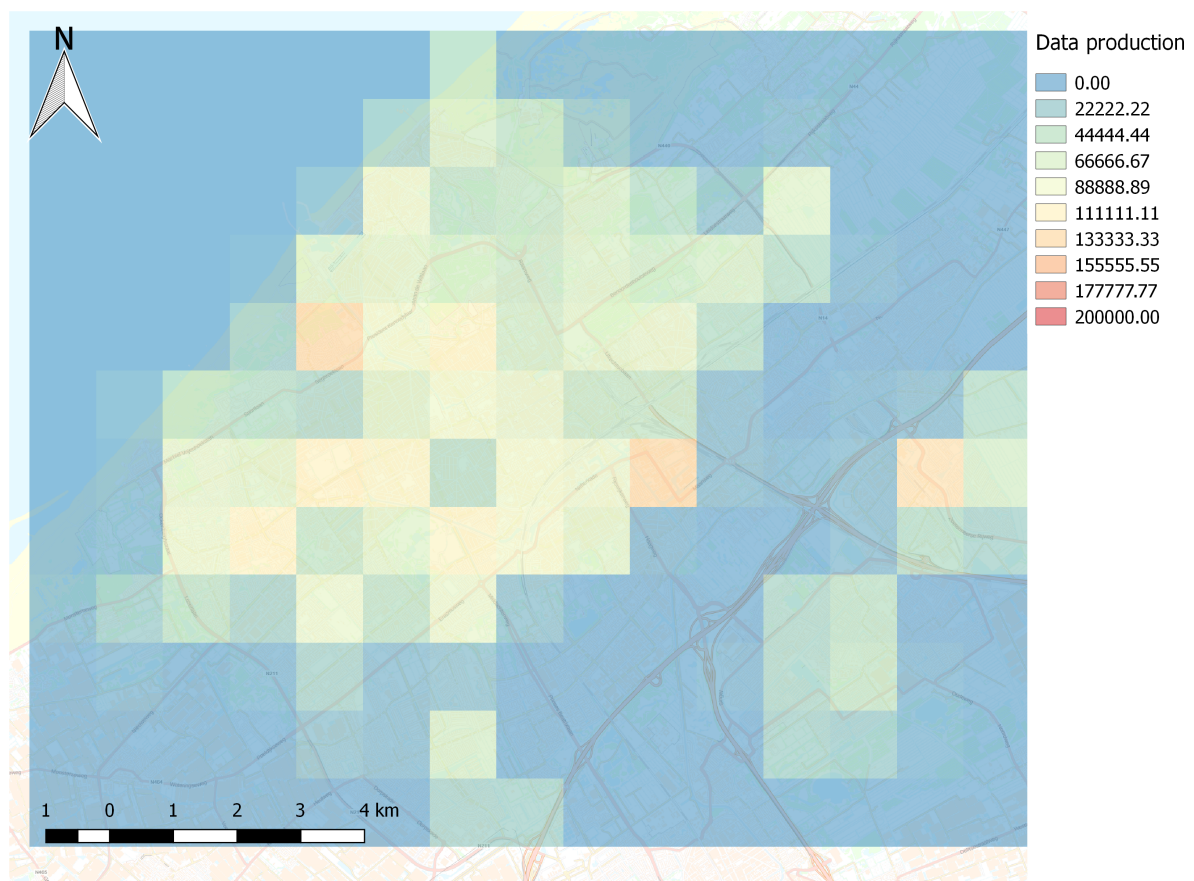
Figure 5.9: Simulation part B: minimum scenario data production due to sensors (resolution 1000mx1000m)

5.1.3. Simulation part C

Simulation part C involves the optimisation of the capital expenditures through relocating sensor types within the boundaries of the placement rules. As can be seen in the modelling example in figure 4.2, often multiple items of street furniture qualify to meet the requirements set in the placement rules. Simulation part C tries to find the items of street furniture that meet the requirements in a cost-optimal way.

Table 5.11: Simulation part C: comparison of investment cost saving per sensor type due to placement optimisation

n	Name	Absolute	Relative
1	Air quality	0	0
2	Air temperature	0	0
3	Camera	[CONF]	48,7%
4	Garbage level	0	0
5	Ground temperature	0	0
6	Number of people	0	0
7	Number of vehicles	0	0
8	Parking occupation	0	0
9	Sound level	0	0
10	Vehicle speed	0	0
11	Water level	0	0
	Total	[CONF]	48,7%

Table 5.11 shows the absolute and relative benefit of the optimisation compared to the outcome of simulation part B. Because placement optimisation is only useful for sensor types that have a fixed connection, the camera is the only sensor type for which the optimisation yields results. Compared to the cost figure mentioned in table 5.8, the cost-optimisation results in a saving of 48,8% in the city of The Hague. The basis for this cost saving is a reduction in the distance that needs to be covered with additional cabling. The average distance saved per sensor is calculated to be 22,1 meter.

5.1.4. Simulation part D

In order to examine the extent of cost-optimisation, the final part of the simulation strategy involves investigating possible substitutions of telecom links with ad-hoc (sensor to sensor) links. In order to do this, a clustering algorithm is used to identify sensors nodes that are located within a specified maximum distance of each other. In figure 5.10 the sensor locations resulting from the minimum scenario of simulation part C are plotted, with the x and y axis representing the x and y coordinates of the sensor nodes respectively. In figure 5.11, a clustering of sensor nodes is shown with a maximum distance between a node in the cluster to another node in the cluster (d_{max}) of 50 meter. The nodes depicted in the same colour belong to the same cluster, and larger circles represent sinks in the clusters.
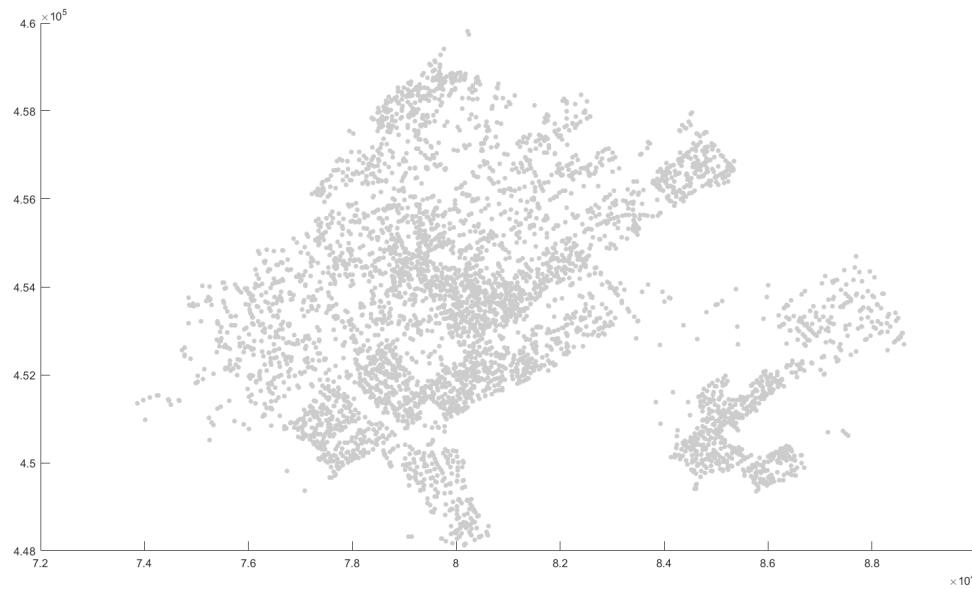
Figure 5.10: Simulation part D: sensor locations resulting from simulation step C used as input for simulation part D
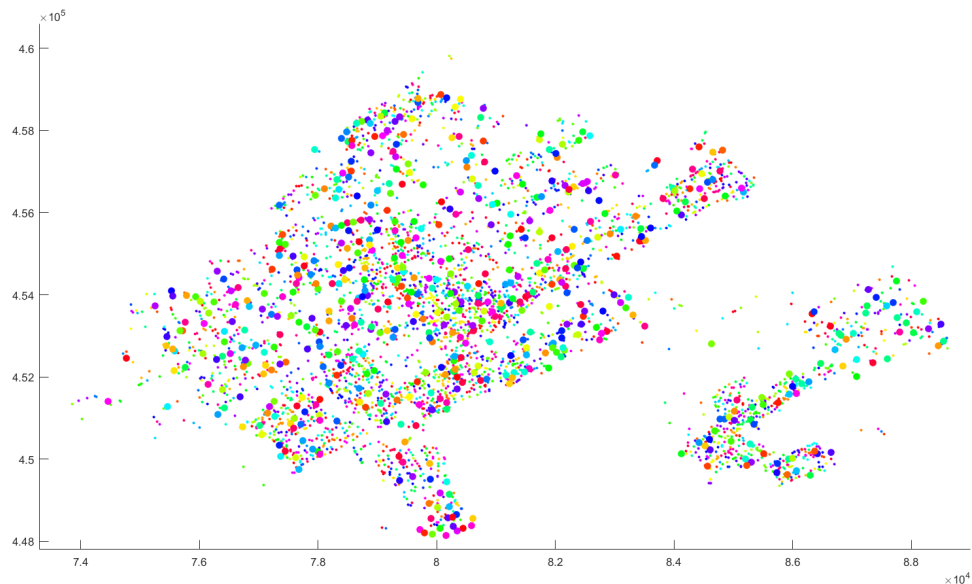
Figure 5.11: Simulation part D: clustering of the sensor nodes resulting from simulation step C, with a specified maximum distance between nodes of 50 meter

The total number of clusters in this plot is 3044, with an average number of 3.44 sensors per cluster. The largest cluster contains 40 sensors. Based on this clustering, links originally used to connect sensor nodes directly to a telecom node can be replaced with a ZigBee connection to the sink node in the cluster. Table 5.12 shows the operational cost-savings that are achieved with the substitution of telecom links. A noticeable result is that the camera is always assigned the sink function, because it is the only sensor type that always requires a wired connection. It therefore does not directly benefit from link substitution. For the remaining sensor types, the benefit of link substitution lies between 28,5% and 87,8%. The difference is originating from the likelihood that a sensor is deployed within d_{max} of a sink node in the cluster. For example, the sound level sensor, which is deployed in crowded areas, has a high relative cost-saving because it is likely that a camera is deployed within d_{max}. A parking occupation sensor on the other hand is often deployed in relative isolation from other sensor types and therefore only has a cost-saving of 28,5%.

Table 5.12: Simulation part D: Benefit of adding ad-hoc per sensor type for the minimum scenario

n	Name	Absolute	Relative
1	Air quality	81,23	75,2%
2	Air temperature	8,54	63,3%
3	Camera	0	0%
4	Garbage level	92,50	57,1%
5	Ground temperature	169,02	62,6%
6	Number of people	18,96	87,8%
7	Number of vehicles	348,84	32,3%
8	Parking occupation	69,26	28,5%
9	Sound level	3,24	85,7%
10	Vehicle speed	33,69	31,2%
11	Water level	20,22	74,9%
	Total	845,50	9,14%

The total cost-saving takes into account the links that have not been substituted, and is therefore limited to 9.14% when d_{max} is set to 50 meter. The Sensor Placing and Optimisation Tool allows for varying the value of d_{max}. In this simulation a value of $d_{max} = 50$ has been chosen because of the range limitation imposed by the ZigBee technology. Literature sources report a wide range of achievable radio ranges with ZigBee, as discussed in chapter 3. A value of 50 meters is expected by KPN experts to be a realistic value in an urban environment and therefore chosen as a reference for this simulation.

5.2. Sensor data production

Given the results presented in section 5.1, the Sensor Planning and Optimisation Tool can give an estimation of the amount of data produced due to sensors for every pair of coordinates in The Hague. This estimation can be visualised in a 3D plot as depicted in figure 5.12.
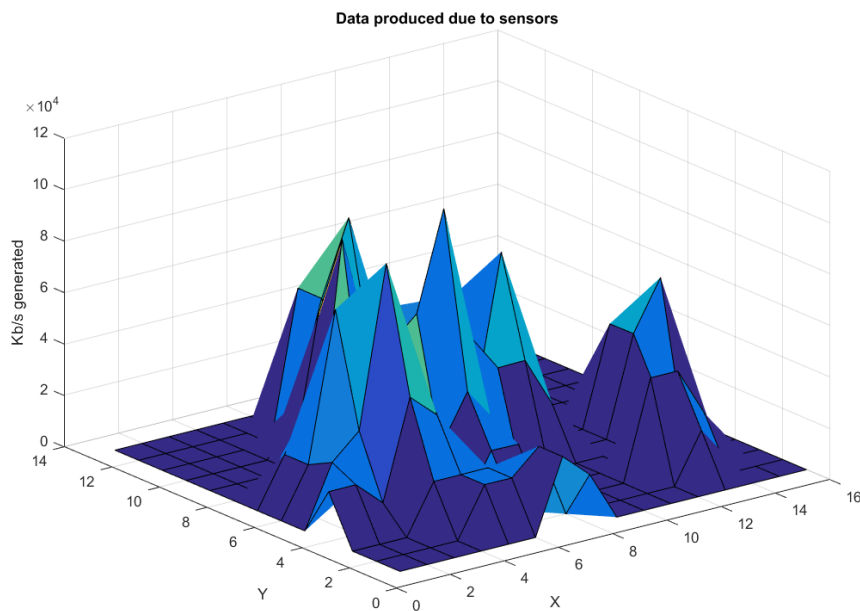
Figure 5.12: 3D visualisation of data production

In order to provide a context to the information shown in figure 5.12, the same data can be plotted on a map of the city of The Hague. An example is shown in figure 5.13 and serves as an aid to users of the simulation tool to identify zones on the map with a large amount of data production. The tool allows for zooming in to specific areas and changing the resolution of the data grid.
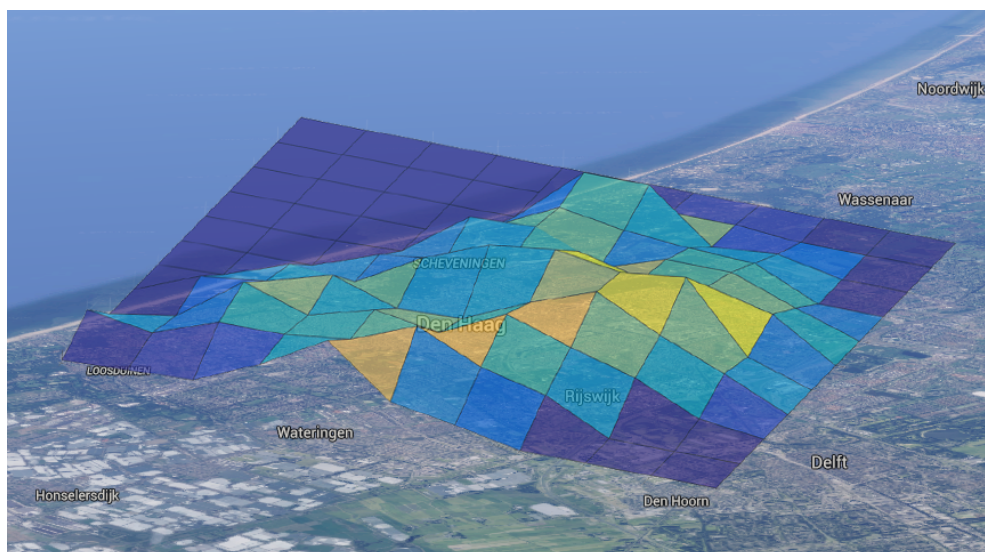
Figure 5.13: A 3D visualisation of the sensor data production plotted on a map of The Hague

5.3. Conclusions

This chapter discusses the results from the simulations performed using the Sensor Planning and Optimisation Tool, that has been developed during this research. Following the simulation strategy outlined in section 4.2.1, and taking into account the available telecommunication access technologies in the city of The Hague, a suggestion for the cost-optimal connection of sensors in the urban public space has been proposed.

The simulation results indicate that, from a cost-perspective, most of the sensor types relevant for use in the urban public space can be connected with cost-efficient LP-WAN technology. However, a remark has to be made about the measurement frequency and transmission latency that are feasible with technology using unlicensed spectrum such as LoRaWAN. In some cases, a dynamic quantity needs to be observed in sufficient resolution and in (near) real time. If buffering of the sensor values leads to unacceptable delay in the transmission, the limitations imposed to the unlicensed spectrum may cause LTE or even a fixed technology to be a more suitable connectivity option. Based on the interviews with municipality experts described in chapter 3, this will likely be the case for the sensors that have been classified in table 5.13 as continuously transmitting.

Table 5.13: Grouping of sensor types into transmission triggers

| Measurement transmission trigger | **Sensor type** | | | | | | | | | | |
	1	2	3	4	5	6	7	8	9	10	11
Event				X				X	X		
Rigid time schedule	X	X			X	X	X		X		X
Continuously			X			X	X		X		

The sensor types that have throughput requirements exceeding the capabilities of wireless access types, are in the city of The Hague best served, from a cost-perspective, by a DSL based connectivity option. The expected required upload throughput is, at the moment, still achievable by using (BV)VDSL. Currently, the low density of fibre access points in the city causes the required investment cost for optical fibre to be significant.

Simulation part C shows that a cost-optimisation based on the location of sensor nodes is able to reduce the total capital expenditure of network infrastructure by 48,8% compared to following the placement rules without optimisation.

The operational expenditures can be reduced by replacing links from sensor nodes to telecom nodes with ad-hoc sensor to sensor links supported by ZigBee, as is shown in simulation part D. This is done by clustering nodes that are geographically close together and assigning a sink within each cluster. The sink node is then capable of relaying data for other sensor nodes within d_{max} of the sink node. A d_{max} value of 50 meter resulted in a cost-saving of 9,14% compared to the total network operational cost from simulation part C.

<div align="right">

6

</div>

Conclusions and recommendations

This chapter presents the answers to the research questions and conclusions from the previous chapters in section 6.1. Recommendations are provided in section 6.2, targeting both telecommunication operators endeavouring into the field of connecting sensors to their existing infrastructure and municipalities investigating deployment of Smart City applications involving sensors. Finally, some directions for future academic and applied work are suggested in section 6.3.

6.1. Main conclusions

This section provides an overview of the main research outcomes and conclusions as discussed in the previous chapters, and formulates an answer to each of the three research questions.

6.1.1. Research question 1

Which types of sensors are promising, now and in the future, for a Dutch municipality like The Hague?

Chapter 3 discusses the analysis performed for the city of The Hague. The research has shown that currently the following 8 sensor types are used actively in the urban public space.

- Air quality sensors
- Induction loop detectors
- Ground water level sensors
- Pneumatic tube detectors

- Radar detectors
- Speed cameras
- Weather stations
- Video cameras

Additional research performed by [103] revealed that other municipalities in the Metropolitan Area Rotterdam The Hague currently employ a comparable set of sensor types.

After analysing the challenges municipalities are dealing with in the urban public space and recognising the trends towards Smart Cities, the conclusion seems justified that an inventory of quantities of interest is more useful to municipalities than an inventory of sensor types. For this reason, the quantities in table 6.1 have been identified as promising for future deployment in the urban public space. The table indicates as well which sensor types could be used to obtain the desired quantities. From table 6.1, it is observed that seven out of the twelve sensor types are already deployed in the urban public space. However, the transition towards future Smart Cities implies that the number of deployed sensors and sensor types is going to increase. Together with municipality experts two sensor deployment scenarios have been constructed, a minimum and a maximum scenario, indicating the number of deployed sensors in the city of The Hague by taking into account future information requirements.

Table 6.1: Sensor types identified as promising for future Smart City deployment

n	Quantity of interest	Sensor type	Why deployed	Currently deployed in The Hague
1	Air quality	Combination	Improve public health	Yes
2	Air temperature	Resistance thermometer	Improve public health	Yes
3	Street view	Camera	Improve public safety	Yes
4	Ground temperature	Laser Resistance thermometer	Prediction of slipperiness Optimising road salting routes Detect melting tarmac Detect expanding bridges or rail road switches	Yes
5	Garbage level	Laser Ultrasound	Optimise garbage collection Prevention of litter	No
6	Number of people	Bluetooth Wi-Fi	City planning Dynamic road signs	No
7	Sound level	Microphone	Improve quality of life	No
8	Vehicle speed	Laser Radar Induction loop	Improve quality of life Assist law enforcement	Yes
9	Vehicle detection	Pneumatic tube Radar	Dynamic road signs, City planning, Evaluation of bicycle measures	Yes
10	Parking space occupation	Infra red Radar	Prevent searching traffic	No
11	Water level on roads	Radar Laser Float switch	Detect sewer overflow Detect tunnel flooding	No

6.1.2. Research question 2

What types of telecommunication access technologies are currently available to support the connection of sensors in public space?

Based on literature review and interviews with KPN experts, this research identified the following telecommunication access technologies as being currently available and suitable for connecting sensors in the urban public space:

- ZigBee

- LoRaWAN

- LTE

- DSL, more specifically the variants VDSL2, VVDSL2 and their versions using pair-bonding.

- Optical fibre

Together, these 5 technologies cover the entire throughput spectrum as shown in figure 1.3 and contain both wired and wireless technologies.

Wired access technologies have the advantage that their operational expenditures do not depend on the amount of data transmitted in a certain time period. This is especially beneficial when large amounts of data have to be transferred from static locations. On the other hand, the initial investments required for wired connections in the public space can become significant with increasing distances. Therefore, wired connections do not seem a likely candidate to connect individual sensors to a telecommunication network. Rather, an ad-hoc approach should be followed where sensors with low throughput requirements wirelessly connect to a sink node that is connected using a wired technology. The sink node function should be assigned to sensor types with high throughput requirements, such as the camera.

6.1.3. Research question 3

Given an amount of sensors of different types and requirements, what is the cost-optimal way of connecting them using existing telecom access technologies?

From the simulations it can be observed that the cost-optimal way of connecting sensors to a telecom network will involve multiple telecom access technologies, based on the type of sensor and the location of the sensor. Most of the sensor types relevant for use in the urban public space can be connected with cost-efficient LP-WAN technology. The research results indicate that the suitability of LPWAN technologies is highly dependent on the required measurement frequency and delay tolerance. In the case of LoRaWAN, where unlicensed spectrum is used for the transmission of data, the transmission duty cycle and maximum power level are limited by regulation. Whenever applications require data to be sent more often than allowed by the duty cycle limitation, LoRaWAN is not the optimal connection technology. When requirements for measurement frequency demand real time transmissions, an LTE connection seems an appropriate substitution for LPWANs. This will likely be the case for the sensor types that have been classified as continuously transmitting in table 6.2. The sensor types that have throughput requirements exceeding the capabilities of wireless access types, are in the city of The Hague best served, from a cost-perspective, by a DSL based connectivity option.

Simulation part C has shown that a cost-optimisation based on the location of sensor nodes is able to reduce the total capital expenditure of network infrastructure by 48,8% compared to following the placement rules without optimisation. The operational expenditures can be reduced by replacing links from sensor nodes to telecom nodes with ad-hoc sensor to sensor links supported by ZigBee, as is shown in simulation part D. This is done by clustering nodes that are geographically close together and assigning a sink within each cluster. The sink node is then capable of relaying data for other sensor nodes within d_{max} of the sink node. A d_{max} value of 50 meter resulted in a cost-saving of 9,14%.

Table 6.2: Grouping of sensor types into transmission triggers

Measurement	Sensor type										
transmission trigger	1	2	3	4	5	6	7	8	9	10	11
Event				X				X		X	
Rigid time schedule	X	X			X	X	X		X		X
Continuously			X			X	X		X		

6.2. Recommendations

This section provides the recommendations resulting from the answers to the research questions and expert sessions. The recommendations are split into two subsections, each targeting one of the main stakeholders in this research: telecommunication operators and municipalities.

6.2.1. Telecommunication operators

1. It is expected that, with evolving technologies as LTE-Advanced and the upcoming standardisation of 5G, current 2G/3G networks will be phased-out within the coming years. This is likely going to pose problems for owners (and operators) of devices, as especially 2G networks are frequently used for the connection of Machine-to-Machine devices. An alternative in the form of currently available LTE networks often leads to higher operational expenses, while higher throughput and lower latencies offered by these networks are often not essential for the operation of the M2M connection. On the other hand new LPWANs, like LoRaWAN, sometimes cannot meet the throughput or real time requirements. Therefore, it is recommended that operators invest in new technologies that bridge the gap between LTE and LPWANs. For example, the new LTE-MTC technology (still in the standardisation process during this research) offers promising characteristics to fill this gap.

2. KPN experts have indicated, in line with conclusions from available data has shown as well, that copper cabling used for the connection of phone boots is often still in place and unused. These former phone boots were often located in public places in the city where large numbers of people passed by, like railway stations and shopping areas. Simulations including the locations of these former phone boots show the possibility to use the former phone boot connections as a means to connect sensors to the telecommunication network.

3. The simulation outcomes indicate that large amounts of (sensor) data will be generated at crossroads within the urban public space. Currently the telecommunication network is capable of appropriately handling this amount of data using the available access technologies. However, the scarcity of optical fibre connections within the city of The Hague may be troublesome if data production grows stronger than expected. Therefore, it is recommended that operators and local governments, e.g. municipalities, jointly investigate the accelerated roll-out of optical fibre within the urban public space. Given the high investment cost associated with such an operation, it may be worthwhile to combine this roll-out with future FttH projects.

4. The simulation tool developed within this research project is still in the prototype phase and not yet suitable for use on a larger (geographical or commercial) scale. It might be interesting for operators to investigate the possibility to continue the further development of this tool to use in commercial offerings to (municipal) customers, to come up with new use cases or to help network planning.

6.2.2. Municipalities

1. The Internet of Things vision addresses the value involved with sharing and combining of data from different sources. Literature review shows that the IoT is often considered as an enabler for Smart City applications. Therefore, it seems right to make sure that information gathered in Smart City applications will be made available as open data to the public unless legitimate reasons prohibit this.

2. Future sensor deployments seem to concentrate along roads and crossroads in particular. It is recommended that municipalities take this into account in public space planning procedures to avoid the cost of later modifications.

3. If the sensor application allows, aggregating different sensor types more closely together offers a more cost-efficient way of connecting the sensors to existing telecommunication access nodes. Aggregating sensors around a sink with a high throughput connection enables to take full advantage of the possibilities offered by ad-hoc networking.

6.3. Future work

This research project aimed to start the development of a cost-optimisation model and tooling for the connection of sensors to a telecom network in the urban public space. This section proposes some of the directions that seem interesting for future work.

1. This thesis' cost-optimisation model has mainly been developed based on interviews, expert sessions and data originating from municipality experts from The Hague municipality and KPN. Validation of part of the results with other municipalities in the Metropolitan Area Rotterdam The Hague has been performed together with [103]. Future research efforts could focus on the validation of the cost-optimisation model in other (Dutch) municipalities or other governmental organisations involved in the management of the public space.

2. As described in chapter 2, the power network has been included in the initial scope of this research project. Due to time constraints and the necessity to reduce the complexity of the project, the power network has been deliberately omitted from the cost-optimisation model during the re-scoping. However, for a complete understanding on optimising sensor deployment in the urban public space, knowledge on the power network is considered essential. It is therefore suggested that future research incorporates the power network in sensor deployment optimisation.

A
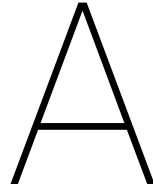
Interview reports and expert sessions

During this research project a number of people with different expertises and relations to the research have been interviewed. Table A.1 shows the interviewees and their function within their organisation. The following pages include the interview reports that have been derived from these interviews. As all interviewees are native Dutch speaker, the interview reports have been made in the Dutch language.

Table A.1: Interviewed experts including organisation and function

Name	Organisation	Function
Sander Kleinstra	The Hague municipality	Manager public lighting
Martijn Peltenburg	The Hague municipality	Policy official digital public space
Jasper Vries	The Hague municipality	Staff traffic management
Douwe Zijlstra	The Hague municipality	Staff engineering office The Hague
Hans Jansen	GGD Haaglanden	Staff living environment
Ruben van Bochove	Nobralux	Projectmanager Zichtenburg pilot
Carly Klein	KPN	Staff Cost Accounting mobile
Walter Knoop	KPN	Quality Manager Mobile networks
Simon Philipsen	KPN	Productmanager LoRa
Loreto Pizarro Silva	KPN	Consultant fixed networks
Sander van de Ree	KPN	Manager Cost Accounting fixed
Willem van Wijck	KPN	Consultant fixed networks

A.1. Martijn Peltenburg

Belangrijkste conclusies gesprek Martijn Peltenburg
5 juli 2016 11:00 – 12:00, Stadhuis Den Haag

Aanwezig: Martijn Peltenburg   Gemeente Den Haag
                Erik Lemmens   TU Delft

Versie concept 0.1

Vragen

1. Heeft Den Haag op dit moment een centraal beleid/visie t.a.v. sensoren in de stad?

    Op dit moment is er geen centraal beleid t.a.v. IoT/SC of sensoren in de stad. Dit is ook niet vreemd gezien de 'hype' rond dit thema pas vrij recent (2015) is ontstaan en de gemeente tijd nodig heeft om hier op te reageren. Het is op dit moment ook niet de prioriteit om met een visie te komen, maar iedereen ziet wel de potentie die de technologie heeft. Het stellen van de 'waarom-vraag' blijft wel heel belangrijk.

    a. ~~Zo ja, hoe luidt deze?~~

    b. Los hiervan, heeft u een persoonlijke visie op sensoren in de stad?

    Martijn gelooft niet zo in de grootschalige uitrol van sensoren in de stad. Sensoren kunnen verbeteringen brengen, maar het is niet de taak van de gemeente om dit soort projecten op te pakken.

    Er is wel een duidelijk verschil tussen sensoren bedoelt voor procesoptimalisatie binnen de gemeente en sensoren bedoelt voor het gebruik in Smart City achtige toepassingen. Voor de eerste groep is een sluitende business-case mogelijk, voor de tweede vaak niet. Dit is wel een vereiste.

    Martijn geeft het voorbeeld van 2000 nieuwe bomen die ieder jaar geplant worden, waarvan 10-20% sneuvelt in het eerste jaar. Het gebruik van sensoren zou er in dit geval voor kunnen zorgen dat er meer bomen het eerste jaar doorkomen door het meten van de grondvochtigheid ter plaatse.

    Een ander voorbeeld is een proef die vorig jaar (Q4 2015) in Den Haag is gehouden met sensoren voor het meten van wegdektemperatuur. Dit is uiteindelijk gestopt omdat de waarom-vraag onvoldoende beantwoord was en de kosten erg hoog waren.

2. In het ideale geval, welke typen sensoren zou een gemeente kunnen gebruiken om bij te dragen aan haar doelstellingen?

    Heel breed, hier is niet direct een antwoord op te geven.

3. ~~Hoeveel van deze typen zijn realistisch gezien binnen 5 jaar te plaatsen, mede gezien de huidige wet/regelgeving?~~

    a. ~~Welke use-case heeft de hoogste prioriteit?~~

    b. ~~Wanneer zou deze gereed kunnen zijn?~~

    c. *Alle sensoren in op de lijst van eerste selectie zijn potentieel geschikt voor gebruik door de gemeente voor het optimaliseren van haar processen*

4. ~~Hoeveel sensoren zou de gemeente Den Haag maximaal/minimaal nodig hebben?~~

    a. ~~Zijn er gemeenten met andere wensen, zo ver u weet?~~

    b. ~~[Reflectie eerste inschatting]~~

5. ~~Zit er een verschil in het plaatsen van sensoren in verschillende wijktypen?~~

    a. ~~Zo ja, welke wijktypen zijn hierin te onderscheiden?~~

    b. ~~Wat zouden de eisen zijn van deze verschillende wijktypen t.a.v. sensoren~~

6. Hoe zou een gemeente de grootschalige uitrol van sensoren in de stad kunnen organiseren?

    a. Welke partijen/afdelingen moeten hierbij betrokken worden?

    Voor het doen van pilots en experimenten is het op dit moment makkelijker om iedere afdeling dit zelf te laten organiseren zonder centrale sturing op te zetten.

    b. Hoe ziet de gemeente haar eigen rol en verantwoordelijkheid?

    In principe overlaten aan de markt. Overheid heeft geen goede reputatie als het gaat om grote ICT projecten.

    c. Wie beheert de gegenereerde data en gegenereerde informatie?

    Zou uitgezocht moeten worden

    d. Moet de data opengesteld worden voor 3^e partijen?

    In principe wel

Verder besproken

De gemeente zou het aan 3^e partijen kunnen toestaan om zelf sensornetwerken uit te rollen, maar hierbij is ook de waarom vraag belangrijk.

Onderschat niet hoe ingewikkeld het is om projecten in de buitenruimte uit te voeren. Achteraf installeren in bestaand straatmeubilair is altijd duurder en kan problemen geven bij beheer/onderhoud. De businesscase voor sensoren is alleen sluitend bij installatie in nieuwe objecten.

Bij het starten van projecten zou de leverancier een prototype binnen 14 dagen klaar moeten kunnen zijn, als dat niet lukt is het waarschijnlijk geen kansrijk idee.

A.2. Jasper Vries

Data Verkeersmanagement (versie 1 juli 2016)

Naam	V-Log
Wat	Log-informatie van verkeersregelinstallaties
Primair doel	Analyseren van werking van verkeersregelinstallatie
Secundaire doelen	Tellen van voertuigpassages; Genereren van triggers voor automatische maatregelen dynamisch verkeersmanagement.
Inhoud	V-Log data bevat toestandswijzigingen van de onderdelen van een verkeersregelinstallatie, voor zowel interne signalen, ingangssignalen als uitgangssignalen. Onder ingangssignalen worden onder andere verstaan de toestand van voertuigdetectiemiddelen (lussen, drukknoppen, selectieve detectie van openbaar vervoer en andere detectiemethoden) en externe ingangssignalen van andere systemen (waaronder wissels, tunnels, bruggen). Onder uitgangssignalen valt onder andere de stand van de verkeerslichten.
Dataformaat	Hexadecimaal
Documentatie	Beschikbaar
Beschikbaarheid	±200 verkeersregelinstallaties in Den Haag
Betrouwbaarheid	Betrouwbaarheid algemeen: benadert 100%. Betrouwbaarheid koplussen voor intensiteitbepaling: bij 69% van 112 onderzochte lussen valt de afwijking de gemeten intensiteit binnen 10% van de werkelijke intensiteit.
Meetcompleetheid[1]	Mediaan: 97,8% (juli 2015-juni 2016)
Actueel	Nee
Historisch	Ja
Opmerkingen	Vergt veel handmatig uitzoekwerk per installatie om de data geautomatiseerd te kunnen verwerken.
Open data	Nee, wordt aan gewerkt op landelijk niveau.

Naam	Reistijden
Wat	Reistijdmeting van wegverkeer op hoofdroutes
Primair doel	Inzicht in actuele verkeersdoorstroming voor dynamisch verkeersmanagement
Secundaire doelen	Analyseren van historische data voor (dynamisch) verkeersmanagement
Inhoud	Gemiddelde reistijd van passerende wegvoertuigen op trajectniveau.
Dataformaat	DATEX-II (XML)
Documentatie	Beschikbaar
Beschikbaarheid	±90 trajecten in Den Haag
Betrouwbaarheid	Afhankelijk van inwintechniek.
Meetcompleetheid	Kentekenherkenning: mediaan 72% Bluetooth: mediaan 47% (jan-mei 2014 werkdagen 7:00-20:00 uur)
Actueel	Ja
Historisch	Ja
Frequentie	1 minuut
Opmerkingen	Locatiereferentie niet-triviaal

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[1] Meetcompleetheid: aantal geregistreerde datapunten in een periode ten opzichte van het theoretisch maximum aantal datapunten in dezelfde periode.

| Open data | Ja, via Nationale Databank Wegverkeersgegevens. http://www.ndw.nu/ |

Naam	Parkeerdata Scheveningen
Wat	Bezettingsgraden en in/uitstroom van parkeergarages en terrein Scheveningen
Primair doel	Aansturing parkeerverwijssysteem
Secundaire doelen	Beschikbaarheid parkeerplaatsen tonen op denhaag.com Beschikbaarheid parkeerplaatsen tonen op dynamische routeinformatiepanelen.
Inhoud	Actuele bezetting en instroom/uitstroom per parkeergelegenheid. Onderscheid wel/geen abonnementshouder.
Dataformaat	Historisch: hexadecimaal; actueel: niet-gestandaardiseerd XML of JSON
Documentatie	Beschikbaar
Beschikbaarheid	3 garages en 1 parkeerterrein op Scheveningen
Betrouwbaarheid	Onbekend. Dezelfde informatie wordt voor parkeerverwijssysteem gebruikt, dus wel uniform.
Meetcompleetheid	85% (juli 2015-juni 2016)
Actueel	Ja
Historisch	Ja
Frequentie	1 minuut
Opmerkingen	Data is eigendom van Beheerskantoor Scheveningen. Beschikbaar gesteld aan de gemeente voor specifieke doelen. Kan niet zonder toestemming Beheerskantoor Scheveningen aan derden worden verstrekt. Toestemming dient door derden zelf bij Beheerskantoor Scheveningen verkregen te worden.
Open data	Nee

Verwacht: bezettingsgraad Biesieklette fietsenstallingen.

A.3. Douwe Zijlstra

Meeting research Sensor Netwerken in Den Haag

5 februari 2016 13:00 – 15:00, Stadhuis Den Haag

Sander Klijnstra	Den Haag
Douwe Zijlstra	Den Haag
Rik Budel	KPN
Edgar van Boven	KPN/TU Delft
Erik Lemmens	KPN/TU Delft

Doel van het gesprek is een kennismaking tussen gemeente Den Haag en KPN/TU Delft over het afstudeeronderzoek van Erik Lemmens met als titel *Interdependent Complex Networks of Sensors, Telecom and Power*. Aan bod komen de doelstellingen van Den Haag met betrekking tot openbare verlichting en de combinatie met sensoren.

Den Haag heeft het gebied Zichterburg, Kerketuinen, Dekkershoek (ZKD) aangewezen als gebied waar lantaarnpalen vervangen gaan worden en waar geëxperimenteerd kan worden met sensoren. In dit gebied zijn ongeveer 100 lantaarnpalen die vervangen gaan worden. Het is lange tijd enkel de doelstelling geweest om met het vervangen van lantaarnpalen en armaturen het energieverbruik omlaag te krijgen en zo Europese doelstellingen te halen, echter de voordelen van het combineren van deze noodzakelijke vervanging met het installeren van sensoren in de publieke ruimte zijn duidelijk. De gemeente ziet het aansluiten van deze sensoren op data communicatie infrastructuur als belangrijk knelpunt in de grootschalige uitrol van sensoren in de publieke ruimte.

Voor de pilot zullen de lantaarnpalen in ZKD permanent van spanning worden voorzien. Een tweede pilot met stroomvoorziening via DC wordt ook gehouden, echter voor ZKD wordt deze techniek nog 'te jong' bevonden door gemeente Den Haag.

De gemeente houdt nadrukkelijk ook rekening met toekomstige ontwikkelingen als het plaatsen van small-cells in de publieke ruimte en zou hier in de pilot graag ervaring mee opdoen. De visie is dat nieuwe toepassingen zouden moeten worden ontwikkeld in een consortium van partijen, niet enkel door de gemeente of door 1 private partij. Ook de versnipperde infrastructuur op dit moment is geen wenselijke situatie, iedere partij heeft zijn eigen kabels en leidingen en graafwerkzaamheden worden inefficiënt uitgevoerd.

Gesprekken met een beperkt aantal fabrikanten van lantaarnpalen, armaturen en sensoren zijn momenteel gaande om de verdere uitwerking van de pilot vorm te geven. Gedacht wordt aan de volgende sensoren: wegdektemperatuur, verkeerstelling, luchtvervuiling

Met betrekking tot de voorgestelde onderzoeksvragen, geeft gemeente Den Haag de tip om standaardisatie van de gebruikte koppeling tussen fysieke hardware in de lantaarnpaal en het telecommunicatienetwerk te onderzoeken. Voor grootschalige uitrol en flexibele toepassingen is dit essentieel. Verder is differentiatie naar typen gemeentelijke gebieden vereist om een universeel toepasbaar model te maken dat geschikt is voor gebruik binnen een gehele gemeente. Hierbij kan gedacht worden aan onderscheid tussen woonzones, winkelgebieden, toeristische gebieden, industriële gebieden en verkeersaders. Specifiek voor Den Haag is ook de internationale zone van belang.

Ook het benaderen van de HTM is aan te raden omdat deze partij een groot aantal bovenleidingmasten heeft in het centrum van de stad waar de hoeveelheid lichtmasten juist beperkt is. Deze bovenleidingmasten hebben de ideale hoogte voor het ophangen van small-cells. HTM is ook bezig om een eigen glasvezel netwerk uit te rollen naast / in te buurt van de tramrails in de stad.

Voor het onderzoek zal het noodzakelijk zijn interviews te houden met experts van de gemeente Den Haag op het gebied van openbare verlichting. De gemeente heeft in het gesprek haar medewerking hiervoor toegezegd.

Verslag meeting onderzoek Den Haag

3 mei 2016 10:00 – 12:00, Stadhuis Den Haag

Douwe Zijlstra	Den Haag
Edgar van Boven	KPN/TU Delft
Erik Lemmens	KPN/TU Delft

Versie v1.0
Status: Vertrouwelijk

Samenvatting

Deze afspraak is een vervolg op de telefonische afspraak met Sander Klijnstra van 20 april (waar Douwe niet bij kon zijn vanwege verlof). Dit is een inhoudelijke meeting waarin details over de Zichtenburg pilot zijn besproken, de voortgang van het project vanuit KPN is gedeeld en actiepunten zijn vastgesteld voor de komende tijd. Een nieuwe afspraak is gepland op 18 mei, Stadhuis Den Haag.

Zichtenburg pilot

Inmiddels nadert de opening van de pilot in Zichtenburg. Deze staat gepland voor 2 juni. Douwe heeft een kaart laten zien waarop de verschillende typen sensoren die geplaatst gaan worden zijn ingetekend. Op dit moment is gekozen voor 11 typen:

- Luchtkwaliteit
- Luchttemperatuur
- Grondtemperatuur (wegdek)
- Vuilniveau (afvalbakken)
- Geluidsniveau
- Snelheid

- Telling mensen
- Telling voertuigen
- Detectie gebruikers *
- Parkeerdetectie
- Waterniveau wegdek

* Het is Douwe niet geheel duidelijk wat het verschil is met de twee andere genoemde tellingen

De sensoren en armaturen worden geleverd door 7 leveranciers:

- Ziut
- Philips
- Tvilight
- Citytec

- Orange lighting
- Smartnodes
- Elspec

De communicatie vindt plaats via het open ALiS protocol[1]. Bij de pilot worden (nog) geen camera's meegenomen omdat die teveel data genereren voor ALiS en eerst gekeken moet worden of deze opzet gaat werken.

Oorspronkelijk was het plan om een deel van het gebied te voorzien van DC. Dit is uitgesteld vanwege verschillende kabeldiktes en de constatering dat de moffen die deze kabels verbinden niet goed met DC overweg kunnen. Ook kan de apparatuur van de leverancier niet het gevraagde vermogen leveren.

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[1] https://www.alis.foundation/wp-content/uploads/2015/09/ALiS-specification-V1_2-2015-7-9.pdf

Dataverzameling in Den Haag

Douwe geeft een indicatie van de hoeveelheid data die al door diverse diensten binnen en buiten de gemeente Den Haag verzameld wordt. (* Douwe stuurt een recent overzicht van de verschillende afdelingen die onder de Dienst Stadsbeheer vallen). Douwe noemt de onderstaande partijen die eigen infrastructuur (met camera's) gebruiken in de stad:

- Rijksvastgoedbedrijf; verantwoordelijk voor de beveiliging van ministeries in het centrum, tribunalen en Eurojust en bezig met het aanleggen van een beveiligingsring.
- HTM; heeft camera's op alle stations en voertuigen. Onder het stadhuis in de tramtunnel bevindt zich een controlecentrum waar alle beelden permanent bekeken worden. Op station Hollands Spoor komt een nieuwe "Tophalte"[2], met 7 camera's. Deze zullen met een nieuwe glasvezelverbinding aangesloten worden op een centrale in het stationsgebouw. Alle camera's krijgen een eigen glasvezel en moeten een resolutie hebben die geschikt is voor gezichtsherkenning.
- Dynamisch verkeersmanagement Den Haag; 250 VRI's met eigen netwerk en camera's, verkeerstellingen en snelheidsmetingen met lussen in het wegdek bij VRI's. Deze worden ook gebruikt voor roodlichtcontrole.
- NDW; heeft camera's voor verkeerstellingen
- Politie; eigen camera netwerk dat wordt uitbesteed aan een bedrijf dat alle aanleg en onderhoud uitvoert.

Elektriciteitsnetwerk in Den Haag

Douwe heeft een kort college gegeven over de opzet van de energievoorziening van de openbare verlichting in Den Haag. Eneco heeft een straatkast met 6 groepen van 4 aders (3 fasen, 1 nul; 4 x 6 of 4 x 2,5). Deze aders lopen vanaf de staatkast de straat in en de lantaarnpalen zijn hierop aangesloten via een aftakmof. De lantaarnpalen maken om en om gebruik van de 3 fasen. De lengte is maximaal 350 meter om te zorgen dat de zekering in werking treedt in het geval van kortsluiting. In principe is het net niet permanent voorzien van spanning. Het komt wel voor dat 1 van de fasen gebruikt wordt voor het aansluiten van andere apparatuur, zoals een camera. Deze is dan wel permanent voorzien van spanning. Voor de pilot in Zichtenburg wordt het net wel permanent voorzien van spanning.

Vroeger werd het net ook wel aangelegd als waterval schakeling, maar toekomstige aansluitingen zullen allemaal als ster worden uitgevoerd. Douwe gaat overleggen met Sander of de tekeningen van het elektriciteitsnetwerk gedeeld kunnen worden. Ze zijn ook opvraagbaar via het kadaster tegen betaling van €25.

Douwe ziet op lange termijn een standaardkast die gebruikt kan worden door meerdere aanbieders die in die straat/wijk kasten hebben staan. Doel is om de grote verscheidenheid aan kasten terug te dringen. Een vraag is hoeveel ruimte (m^2) KPN in zo'n nieuwe standaardkast nodig zou hebben. Ook zou Douwe graag zien dat er standaard bij de aanleg of onderhoud van kabels in de grond een buis voor glasvezel meegenomen wordt, omdat graven de grootste kostenpost is. Douwe noemde het voorbeeld van een 4 x 6 kabel die €4 per meter kost. Aanleg kost €20 euro per meter, waarvan €15 loonkosten. Ook is het zeer ongewenst dat pas gelegd straatwerk weer opnieuw opengebroken moet worden omdat een andere partij werkzaamheden wil doen, al dan niet vanwege een storing.

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[2] http://denhaag.nl/web/wcbservlet/com.gxwebmanager.gxpublic.risbis.fileservlet?fileid=8b2a747d-d55e-4cb5-83b9-65d10880d025

Voortgang onderzoek Erik

De afgelopen periode stond vooral in het teken van het verzamelen van informatie. Op dit moment is de relevante informatie over het KPN netwerk in het pilotgebied ZKD zo goed als compleet (kostprijzen, kabelliggingen, verdelers, capaciteit en vrije aansluitingen van voormalig telefooncellen). Er is een start gemaakt met het maken van het rekenmodel waarin deze gegevens gebruikt gaan worden.

Op dit moment is het van belang om een beeld te krijgen van de behoefte aan verschillende typen sensoren en de eisen die daaraan gesteld worden (bijv. installatiehoogte, bandbreedte, uitleesfrequentie enz.), met name voor de onderzoeksvragen 1 en 2. De Excel sheet die met Douwe gedeeld is geeft een indicatie van de richtingen waarvan we denken dat ze belangrijk zijn. De vraag is of Douwe dit van commentaar kan voorzien en eventueel aanvullen. Douwe vertelt dat Den Haag vijf typen wijken onderscheidt, die zeer waarschijnlijk een andere behoefte aan sensoren zullen gaan hebben. Dit zijn

1. Hotspots; Centrum en Scheveningse kust
2. Historische gebieden
3. Doorgaande route en verkeersfunctie
4. Woonwijken
5. Bedrijventerreinen

We hebben contact gehad met de gemeente Zeist om, als middelgrote gemeente, mee te denken over de behoefte aan sensoren. Douwe stelt voor om ook Breda te betrekken omdat deze gemeente nu ook aan het nadenken is over Smart City toepassingen. We moeten oppassen dat het onderzoek niet te groot/breed wordt. Edgar heeft voorgesteld om studenten in de zomer stage te laten lopen op dit onderwerp om zo wat werk te kunnen verdelen (o.a. het uitvoeren van interviews).

NDA

Er is 29 april een handleiding NDA gemaakt en gedeeld waarin is voorgesteld wat wel en wat niet onder het NDA valt. Het verzoek aan Sander en Douwe is om deze waar nodig aan te vullen namens gemeente Den Haag.

Verslag meeting onderzoek Den Haag

18 mei 2016 13:00 – 15:00, Stadhuis Den Haag

Douwe Zijlstra   Den Haag
Edgar van Boven   KPN/TU Delft
Erik Lemmens   KPN/TU Delft

Versie 0.2
Status: Vertrouwelijk

Samenvatting

Vervolg op de ontmoeting van 3 mei, met updates over de Zichtenburg pilot en bespreken van een aantal onderzoeksresultaten. Douwe gaat zijn best doen om sneller te reageren en zal ook aan Sander vragen om vaart achter het NDA te zetten. Volgende afspraak is gepland op 2 juni, tevens de dag van de Zichtenburg pilot test.

Zichtenburg pilot

De technische installatie van sensoren in Zichtenburg is nu gereed (figuur 1). Op 2 juni vind de eerste test plaats om te zien in hoeverre het werkt en welke data er beschikbaar komt via het ALiS protocol. Douwe gaat navragen of Edgar en Erik daarbij kunnen zijn. Hierna wordt de belangstelling voor deze data bij de verschillende gemeentelijke afdelingen gepolst.

Figuur 1: Pilotgebied met locaties lantaarnpalen

Sensorbehoefte Den Haag

Op termijn ziet Douwe een scenario ontstaan waarbij er op iedere straathoek sensoren/camera's hangen die alle richtingen bestrijken. In lange straten zou ook om de 150 meter nog een camera geplaatst kunnen worden. De meest toekomst vaste connectie is een glasvezel vanwege de grootst denkbare beschikbare bandbreedte ten opzichte van alle andere access vormen (glasvezel, tenzij). Eventueel kan een verbinding zelfs redundant uitgevoerd worden, bijvoorbeeld op belangrijke of vandalismegevoelige plaatsen. De benodigde investeringen hiervoor volgen uit het rekenmodel waarin onder andere het glasvezel tenzij scenario gesimuleerd kan worden. Douwe heeft wel aangegeven dat (in dit stadium van het onderzoek) wat hem betreft de investeringskosten geen belemmering moeten zijn voor functionaliteit.

De dienst Bereikbaarheid & Verkeersmanagement, onderdeel van de Dienst Stedelijk Beheer, heeft het plan om een eigen systeem met sensoren op te gaan zetten, om zo de status van borden en VRI's te kunnen monitoren. Dit wil men onafhankelijk van andere diensten gaan opzetten. Volgens Douwe is dit geen goed idee en is het beter om dit probleem samen met andere diensten aan te pakken, hier gaat hij nog een gesprek over voeren. Dit illustreert de fragmentatie binnen de organisatie; er is geen gezamenlijke Smart City strategie/visie. Douwe schetst een visie waarbij de dienst openbare verlichting een generieke sensorfaciliteit gaat bieden, waarbij de lantaarnpaal beschikbaar gesteld wordt aan andere partijen. Hierbij wordt aangeboden:

- Installatiemogelijkheid in de lantaarnpaal
- USB aansluiting (5V; 0.9A max bij USB3.0)
- 24x7 gelijkspanning
- Dataverbinding

Interviewlijst

Douwe heeft een organogram van de gemeente doorgestuurd (zie bijlage). Om de sensor behoefte van Den Haag beter in kaart te kunnen brengen, heeft Douwe de volgende mensen genoemd als mogelijk interessant om te interviewen:

- Martijn Peltenburg
- Ruben Benjamin
- Jan Peter Vaalburg (Elspec)
- Ruben van Bochove (Nobralux)

Douwe gaat Erik introduceren bij deze mensen om het regelen van een interview te vergemakkelijken (inmiddels al gebeurt, waarvoor dank). In de bijlage zijn alle namen opgenomen die tot nu toe zijn genoemd in eerdere gesprekken met o.a. Sander.

Model

Douwe herkent zich in de ontleding van sensoren in de "5 W's": Welke sensor, Wat wordt er gemeten, Waar bevindt de sensor zich (x, y, z), Waarin bevindt de sensor zich en Wanneer (hoe vaak) wordt er gemeten. Deze ontleding is bedoeld om duidelijkheid te scheppen in de terminologie die gebruikt wordt om sensortypen, grootheden, locaties en plaatsen aan te duiden, omdat dat nu vaak door elkaar gebruikt wordt in publicaties. Douwe gaat zijn best doen om het Excel template dat hiervoor gestuurd is te vullen voor de sensoren in de Zichtenburg pilot.

Een ander aspect dat aan de orde gaat komen is optimale spreiding van sensoren over de stad. Dit zal gaan afhangen van het type sensor, maar verder is hier nog niet een goed beeld bij. Hier zullen de interviews met verschillende mensen bij gaan helpen.

Concept verslag meeting onderzoek Den Haag

2 juni 2016 9:30 – 12:00, Stadhuis Den Haag

Aanwezig:	Douwe Zijlstra	Den Haag
	Edgar van Boven	KPN/TU Delft
	Erik Lemmens	KPN/TU Delft
CC:	Sander Klijnstra	Den Haag
	Rik Budel	KPN

Versie 0.2
Status: Vertrouwelijk

Samenvatting

Vervolg op de ontmoeting van 18 mei. Besproken is schatting van minimale en maximale aantallen sensoren voor Den Haag, de ontleding van sensoren in 5 W's en de status van het NDA. Een vervolgafspraak is gepland voor woensdag 22 juni, 13:00 – 15:00 op het stadhuis in Den Haag.

Zichtenburg pilot

Vanmiddag is de officiële start van de pilot in Zichtenburg, waar een zestal leveranciers die de sensor installatie geleverd hebben bij aanwezig zullen zijn. Douwe verwacht dat de pilot ongeveer 6 maanden gaat duren, mede vanwege het feit dat de water- en bodemmetingen afhankelijk zijn van het weer en dit is lastig te plannen. Volgende stappen zijn het beschikbaar maken van data aan andere partijen en onderzoeken of de lantaarnpalen ook uitgerust kunnen worden met een laadvoorziening voor elektrische voertuigen.

Discussie 5 (inmiddels 6) W's

De eerste vraag is wat er precies bedoeld wordt met continu meten. Douwe ziet dit als 24 uur per dag, waarbij bijvoorbeeld om de 5 minuten een meetwaarde verstuurd wordt. De komende tijd wordt uitgezocht wat de eisen zijn van verschillende partijen met betrekking tot meetfrequentie en of de sensoren zelf datatransport initiëren of dat een centraal punt de data moet opvragen.

Douwe voorziet een toekomst waarin de rijksoverheid gemeenten wettelijk verplicht om luchtkwaliteit te meten met sensoren en data aan te leveren op een gestandaardiseerde (evt. ook gecertificeerde) manier.

De sensor "detectie gebruikers" is uit de lijst geschrapt.

Een zesde W is toegevoegd aan de lijst, namelijk het waarom van het meten. Verschillende partijen kunnen andere belangen hebben bij het meten van bepaalde grootheden, en andere informatie dan in eerste instantie voorzien kan wellicht ook interessant blijken te zijn voor nieuwe partijen (bijvangst).

Wellicht kunnen de snelheidsmeting en voertuigtelling gecombineerd worden, omdat iedere meting van snelheid automatisch een voertuig betekent, plus dat de snelheid ook het type voertuig kan bepalen. In Zichtenburg wordt dit nog niet gecombineerd.

Over 5 jaar is waarschijnlijk heel Den Haag betaald parkeren.

Concept verslag meeting onderzoek Den Haag

22 juni 2016 13:00 – 14:30, Stadhuis Den Haag

Aanwezig:	Douwe Zijlstra	Den Haag
	Edgar van Boven	KPN/TU Delft
	Erik Lemmens	KPN/TU Delft
CC:	Sander Klijnstra	Den Haag
	Rik Budel	KPN

Versie 0.1
Status: Vertrouwelijk

Samenvatting

Vervolg op de ontmoeting van 2 juni. Besproken is schatting van minimale en maximale aantallen sensoren voor Den Haag, de ontleding van sensoren in 6 W's en de status van het NDA. Een vervolgafspraak is gepland voor maandag 4 juli, 13:00 – 15:00 op het stadhuis in Den Haag.

Discussie 6 W's en inventarisatie sensoren

De resultaten van de lopende discussie over minimale en maximale aantallen sensoren die gebruikt gaan worden in het rekenmodel staan in de volgende tabel. Deze tabel zal ook aangeboden worden aan de te interviewen personen van de gemeente Den Haag.

Type sensor	Min	Max	Waar	Waarom
Luchtkwaliteit	**Actie Douwe**	**Actie Douwe**	Verkeerswegen, 100m de wijk in	Volksgezondheid
Luchttemperatuur (+ luchtvochtigheid en druk)	5 sensors in 5 hotspots	(mogelijk meer hotspots)	Binnenstad, strand	Volksgezondheid Hittegolf alarm
Grondtemperatuur	ong. 1000	Alle op- en afritten Alle wegen met hoogte verschil	Viaducten en bruggen met verkeersfunctie + tramwissels Wegen met hoogteverschil	Voorspellen gladheid en strooiroutes, smeltend asfalt, uitzettende bruggen / wissels
Afval	300 ORACS en milieueilanden Geen prullenbakken	Alle milieu-Eilanden en alle ORACS Geen Prullenbakken	ORACS (5500 – 7000 Worden geplaatst waar geen ruimte is voor kliko, max 150m lopen 1x oversteken), glas, kleding, papier, plastic, blik, melkpakken Milieueilanden	Efficiënt inzetten vuilniswagens Voorkomen zwerfafval en afvaltoerisme

1

Geluid	Scheveningen (3), Grote markt (2) Plein (2) Anderen?	+50% t.o.v. minimum scenario	Wegen, spoorwegen (bochten, wissels), uitgaansgebied, kruispunten (250)	Leefbaarheid
Snelheid	200	+50% t.o.v. minimum scenario	Woonwijken met asfaltwegen (ex. Politiecamera's bij VRI)	Leefbaarheid (1^e), handhaving (2^e , bijvangst)
Telling mensen	40	+100% t.o.v. minimum scenario	Uitgaansgebieden, Scheveningen, Winkelgebieden	Stadsplanning, dynamische routes
Telling voertuigen	250 x 8	Ook fietspaden meenemen	VRI locaties, fietspaden	Dynamische wegwijzers, stadsplanning, Effect van fietsmaatregelen bepalen
Parkeren	Drukke winkelgebieden (uitzoeken denhaag.nl)	Alle vakken	Parkeervakken of terreinen (in garages wordt al geteld bij de slagboom)	Voorkomen zoekverkeer Sneller parkeerplaats vinden/reserveren
Waterniveau wegdek	Alle tunnels en onderdoor-gangen		Tunnels, onderdoorgangen (Misschien zijn hier al vlotters aanwezig die waterniveau kunnen meten?)	Meten overstort riool, detectie ondergelopen tunnels
Camera	1000 (ex. politie, HTM, NS, etc.)	Elk kruispunt in de stad	Hoofdwegen, straathoeken	Openbare Orde en Veiligheid

Concept verslag meeting onderzoek Den Haag
4 juli 2016 13:00 – 16:30, Stadhuis Den Haag

Aanwezig: Douwe Zijlstra   Den Haag
               Edgar van Boven   KPN/TU Delft
               Erik Lemmens   KPN/TU Delft

CC: Sander Klijnstra   Den Haag
               Rik Budel   KPN

Status: Vertrouwelijk

Classificering
Het bepalen van de wijktypen blijkt lastiger dan gedacht, omdat de keuze voor de classificering zo
veel mogelijk uniform binnen de gemeente dient te zijn. Iedere afdeling hanteert op dit moment zijn
eigen indelingen (ook voor classificatie van wegen). Op dit moment is de volgende indeling gemaakt:
- Winkelgebied
- Woongebied
- Toeristisch gebied
- Bedrijventerrein
- Hoofdwegen (centrumring, s-wegen, internationale ring)
- Wegen voor 50 km/h en minder

Voor de wegen is de volgende indeling gemaakt:
- Stroomwegen (waaronder de centrumring, s-wegen en internationale ring)
- Gebiedsontsluitingswegen
- Wijkwegen
- Erftoegangswegen

Verkeer
[Wegtypen in Den Haag]

De indeling wordt gemaakt op basis van verkeersintensiteit (classificatie criterium). In volgend
interview met Jasper de Vries kan Erik de vraag voorleggen: Hoe worden wegen ingedeeld en wat zijn
de benamingen? In eerste ontmoeting met Jasper meldde hij dat beelden van ca. 50 camera's van
RWS rond Den Haag kunnen worden bekeken. Verder komen er binnenkort 100 HD camera's bij.

Fietsverkeer is interessant omdat daar nog weinig over bekend is. Den Haag heeft ongeveer 300 km
fietspad waarvan 150 km geschikt voor telling. Als er om de halve kilometer een sensor geplaatst
wordt, geeft dit 300 tot 600 sensoren (indien sensor lussen in beide richtingen). Verder zou het
interessant kunnen zijn om sensoren te gebruiken voor parkeerplaatsen specifiek voor doelgroep
minder validen (gehandicapten) (ca. 100 sensor lussen).

Milieu

Op dit moment heeft gemeente Den Haag geen snuffelpalen meer, maar wel 2 meetstations (Vaillantlaan en ??). Voor het bepalen van luchtkwaliteit worden modellen gebruikt. Douwe denkt dat langs de centrum- en buitenring gemeten zou moeten worden op plaatsen waar veel stoppend verkeer is. Ongeveer 2 sensoren per VRI is het minimum. Als er om de 200 m nog een geplaatst wordt en 200 m de wijk in ook is dat een goed maximum.

Parkeren

Douwe ziet niet zoveel in sensoren in parkeervakken in de wijken. Deze zijn toch voornamelijk bezet en niet primair bedoeld voor bezoekers. Eventueel relevant bij hotspots zoals Scheveningen en de bovengenoemde parkeerplaatsen voor minder validen. Ook een Matrix bord aan de Scheveningse weg kan indiceren of er nog parkeerplaatsen vrij zijn aan de Scheveningse kust.

Overig

De standaard afstand tussen lichtmasten schuift langzaam op van 20 naar 40 meter. De "Waarin" kolom van de sensor ontleding kan breder gemaakt worden dan alleen lichtmasten, ieder stuk straatmeubilair is in principe geschikt (bijv. parkeerverwijssysteem, matrixborden, VRI, …)

Het zou interessant zijn om het waterschap te betrekken bij de vraag over het waterniveau op de weg. Wirdmer van Dam gaat in zijn stage naar verwachting informatie verzamelen bij onder andere Waterschap Delfland en Rijnland (betreffende wegmalen, spuien, effluent leidingen, welke informatie uit sensoren relevant voor Waterschappen aangeleverd vanuit gemeenten).
Aktie is navragen bij Dienst verkeer / ingenieursbureau hoeveel tunnels en onderdoorgangen er zijn in gemeente Den Haag.

Het maximum scenario voertuigtelling kan (zoals besproken met Richard Moerenhout) worden uitgebreid met ca. 125 sensoren in fietspaden (25% * 250 VRI * 2 richtingen).

NDA is getekend, gescand en verspreid door Sander. In onderling overleg worden er betrokkenen toegevoegd op "need to know' basis.

Concept verslag meeting onderzoek Den Haag

6 oktober 2016 13:00 – 15:00, Stadhuis Den Haag

Aanwezig: Douwe Zijlstra   Den Haag
                Edgar van Boven   KPN/TU Delft
                Erik Lemmens   KPN/TU Delft
                Wirdmer van Dam   KPN/TU Delft

Versie 0.3

Update Den Haag Smart City en Zichtenburg pilot
Op 19 oktober is er een afspraak tussen Douwe en Ruben van Bochove over de datawinning bij de Zichtenburg pilot. Op dit moment is er nog een hoop handmatig werk bij het verzamelen van data en wordt er nog geen gebruik gemaakt van het ALiS protocol voor het uitwisselen van sensordata met de gemeente. Elspec heeft moeite met het ontwikkelen van een goede geluidssensor vanwege het bepalen van het stilte referentieniveau.

Er is een pilot in de Wassenaarsestraat in Scheveningen, waar Tvilight slimme verlichting heeft geplaatst die de intensiteit aanpast aan de hoeveelheid mensen op straat. Hier is nog wel een aantal klachten over, zoals dat het licht spontaan van 10% naar 100% gaat. De politie heeft een app om indien nodig het licht op 100% te kunnen zetten.

Naast het project *Kust Gezond* in Scheveningen wordt nu ook een Smart City pilot gestart met een consortium van partijen. Hierbij is het doel om de boulevard slimmer te maken, o.a. met verlichting, camera's, parkeersysteem, laadpalen, geluidsmetingen, tellingen van bezoekers en voertuigen, dynamische reclameschermen. De ontwikkelingen gaan op dit moment snel. Op 9 november moet hiervoor het voorlopig ontwerp klaar zijn en gaat het naar het college. In januari start de bestekfase en is er een Go/No-Go moment. Douwe verwacht hiervoor een Go.

Onderzoek Wirdmer
Wirdmer licht toe waar zijn onderzoek op focust. Hij is bezig met een inventarisatie van sensoren langs rijkswegen en wegcomponenten waaruit het wegennet si opgebouwd door het houden van interviews bij Rijkswaterstaat. Ook schrijft Wirdmer software waarmee verschillende topografische databronnen (o.a. van RWS en het kadaster) wordt gecombineerd. RWS is op dit moment bezig met het onderzoeken van de mogelijkheden van *floating car data* en lijkt daardoor minder in te zetten op het vergroten van het aantal sensoren (meetlussen en radar metingen) langs de weg. Het doel van deze software is een inventarisatie te leveren van de lengte van de wegen en aantallen wegcomponenten (o.a. bruggen, kruispunten) per wegbeheerder en per gemeente in Nederland. Uit deze inventarisatie volgt een schatting van de sensorbehoefte en het data volume langs de wegen in Nederland.

Vragen vanuit het onderzoek van Erik
- Plaatsing van sensoren
    - Grondtemperatuur in ieder geval bij hellende vlakken op de 6 sterfietsroutes. Bruggen en viaducten worden het eerste glad omdat er wind onderdoor kan waaien. Drie sensoren aan elke kant van het viaduct/brug is nodig om te kunnen voorspellen of het glad is op de brug.

- o Waterniveaumeting op laagste punt van tunnels en onderdoorgangen. Het doel is om mensen te waarschuwen en om te kunnen leiden.
- Voor camera's op kruispunten is er nu specifiekere informatie. Dit zijn er vaak 4 maar kunnen er ook 2 zijn (dome camera's). Douwe heeft een boek uitgeleend van het CROW waarin voorschriften staan voor het inrichten van kruispunten.
- Richtingseis
  - o Alleen voor richtcamera's relevant. Nieuwe camera's zijn tegenwoordig allemaal type 'dome' en kunnen dus 360 graden kijken. Voor het model is richting daarom niet zo relevant.
- Werkingsprincipe sensoren
  - o Douwe neemt contact op met Ruben om meer te weten te komen over de specificaties van de gebruikte sensoren in Zichtenburg en komt op deze vraag terug.

Vragen vanuit het onderzoek van Wirdmer
1. Wat is in gemeente Den Haag de huidige situatie van het aantal en type sensoren in de publieke ruimte? Template met ingevuld voorbeeld gemeente Rotterdam is bijgevoegd in de bijlage van dit verslag.
2. Wie is voor gemeente Den Haag de contactpersoon voor inventarisatie van wegcomponenten waaronder de kunstwerken? De kunstwerken omvatten alleen bruggen, viaducten, tunnels) maar niet de kruispunten, fietsoversteekplaatsen en spoorwegovergangen.

A.4. Hans Jansen

Belangrijkste conclusies gesprek Hans Jansen over sensoren
27 juli 2016 13:00 – 14:00, GGD Haaglanden

Aanwezig: Hans Jansen   GGD Haaglanden, Afdeling Leefomgeving
              Erik Lemmens   TU Delft

Versie concept 0.1

De GGD heeft een adviserende taak aan gemeenten, instellingen, bedrijven, scholen etc. In het geval van de afdeling leefomgeving gaat het om het adviseren m.b.t. milieufactoren die invloed hebben op de gezondheid, zoals luchtkwaliteit, bodemkwaliteit, asbest, e.d.

De GGD heeft de volgende 3 punten als prioriteit aangemerkt in zijn beleidsplan:

1. Luchtkwaliteit
2. Geluidshinder
3. Temperatuur in de stad

De grootste relevantie van sensoren voor de GGD zit dan ook in deze domeinen.

Luchtkwaliteit

GGD brengt niet zelf de luchtkwaliteit in kaart, dit is een taak voor de gemeente/provincie.

Op dit moment wordt luchtkwaliteit gemonitord m.b.v. een Nederlands rekenmodel[1] dat is gebaseerd op Europese normen[2] voor luchtkwaliteit. Deze normen zijn, volgens de GGD, echter niet perse maatgevend voor gezonde lucht. De GGD heeft in haar beleid de focus op gevoelige groepen als het gaat om luchtkwaliteit, waaronder kinderen. In een recent advies aan de gemeente is dan ook geadviseerd om geen scholen binnen 50m van een drukke weg te hebben.

Het rekenmodel gebruikt wel input van enkele meetpunten in Den Haag, maar gerapporteerde waarden zijn gebaseerd op berekeningen en niet op deze metingen. Het voordeel hiervan is dat er veel meer punten zijn waarop er een berekening gemaakt kan worden dan dat er punten zijn waarop je kunt meten. Er is wel een apart meetnet voor NOx metingen.

De indicatoren die vaak worden gebruikt om luchtkwaliteit aan te geven zijn

- Fijnstof: PM10, PM2.5 en Roet
- Stikstofoxiden: NO, NO2 (NOx)
- O3, Smog (Alleen in specifieke omstandigheden van belang)

Van deze indicatoren zijn stikstofoxiden het best te relateren aan verkeersintensiteit, en ook het gemakkelijkst en nauwkeurigst te meten met elektronische sensoren. PM10 en PM2.5 zijn ook aanwezig als gevolg van natuurlijke bronnen. Roet heeft ook een sterke verkeersafhankelijkheid, en tevens een grote impact op gezondheid omdat deze deeltjes diep binnendringen in de longen.

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[1] https://www.nsl-monitoring.nl/
[2] http://www.clo.nl/indicatoren/nl0237-nationale-luchtkwaliteit-overzicht-normen

Probleem is dat het lastig te meten is. Voor roet is geen Europese norm beschikbaar. Naarmate verkeer steeds schoner wordt, wordt de bijdrage van verkeer aan het fijnstofniveau in de lucht relatief kleiner. Wat opvalt is dat de bijdrage van hou gestookte verwarmingsinstallaties (open haard, houtkachel) relatief groter wordt en op termijn zelfs de belangrijkste bron kan worden van fijnstof.

Het rekenmodel rekent met daggemiddelden. Het is toegestaan om de norm voor daggemiddelden XX dagen per jaar te overschrijden, afhankelijk van de stof. Het zou waardevol kunnen zijn om gebruik te maken van sensoren om het verloop van de concentraties van de bovengenoemde stoffen te kunnen volgen over het verloop van de dag, om hier gerichter maatregelen mee te kunnen nemen. Hierbij zijn de stikstofoxiden het beste om te meten, vanwege de correlatie met verkeer. Plekken waar dit het meest urgent is zijn bijvoorbeeld scholen, kinderdagverblijven, crèches ed. vanwege de focus op gevoelige groepen. Hiervan zijn er in Den Haag ongeveer 800. Meten verspreid over het gehele grondgebied van de stad heeft geen toegevoegde waarde.

Geluidshinder

Het geluidsniveau in de stad kan invloed hebben op de gezondheid van inwoners en is als zodanig van belang voor de GGD. 25% van de inwoners ervaart geluidsoverlast van de buren. De gezondheidseffecten van geluidsoverlast zijn met name merkbaar bij het verstoren van de nachtrust. Het is dan ook van belang om, als er sensoren opgehangen worden die geluidsniveau gaan meten, deze vooral ook 's nachts te laten werken. Op dit moment is er bij de GGD geen volledig beeld van de geluidsoverlast in Den Haag, omdat klachten omtrent geluid bij de omgevingsdienst binnen komen.

Temperatuur in de stad

Het meten van temperatuur in de stad is vooral van belang vanwege het 'hitte-eiland effect' en de bijbehorende hitte stress in de stad. In de stad is het gemiddeld 8 graden warmer dan in de omliggende gebieden. Dit kan problematisch zijn voor ouderen. Er loopt op dit moment een onderzoek naar het fenomeen hitte stress door o.a. TU Delft en gemeente Den Haag. Doel is om de temperatuurverschillen in de stad te relateren aan kenmerken van de plaatselijke bebouwing. Hierbij zijn betrokken Niels Al namens de gemeente en Franklin van der Hoeven namens TU Delft.

Er zijn eerder pilots geweest met sensoren vanuit de GGD, deze zijn echter altijd stukgelopen op een gebrek aan concrete doelstellingen. De meerwaarde is niet altijd voldoende duidelijk en projecten blijven hangen in de oriëntatie of blijken te complex. Zo is er een project geweest om luchtkwaliteit in huizen te meten (CO_2/CO + temperatuur), omdat hier veel gezondheidseffecten aan gekoppeld zijn. Dit is niet doorgegaan vanwege privacy van de bewoners en omdat het organisatorisch te lastig bleek.

A.5. Ruben van Bochove

Belangrijkste conclusies gesprek Ruben en Erik
21 juni 2016 16:30 – 17:30, Ridderkerk

Aanwezig: Ruben van Bochove   Nobralux   (onafhankelijk adviesbureau voor openbare verlichting)
                 Erik Lemmens   TU Delft

Versie concept 0.1

Samenvatting

Vertrekpunt voor het gesprek is de pilot in de wijk Zichtenburg in de gemeente Den Haag waar verschillende leveranciers van openbare verlichting sensoren hebben opgehangen. De verschillende typen sensoren die gebruikt zijn, zijn geselecteerd op de bijdrage die zij kunnen leveren aan de uitvoering van verantwoordelijkheden van een gemeente. Ook zouden deze sensoren in de toekomst in 80% van de Nederlandse straten terug te vinden kunnen zijn.

In het geval van een verdere uitrol over de stad, is nog niet uitgezocht hoeveel sensoren er noodzakelijk zijn voor een voldoende accuraat beeld van de te meten grootheid. Dit is iets dat afhangt van het type sensor en de wensen van de verantwoordelijke gemeentelijke afdeling(en). Ook is nog niet te zeggen hoeveel data de sensoren produceren. De eisen die gesteld zouden moeten worden aan de verschillende typen sensoren (bijvoorbeeld nauwkeurigheid, resolutie, tolerantie e.d.) zijn in dit stadium niet gespecificeerd. Het doel van de pilot is vooral het laten zien van de mogelijkheden op het gebied van sensoren en het opdoen van ervaring.

De data die gegenereerd wordt door de sensoren, moet getransporteerd worden richting de eindgebruiker. Hiervoor is iedere lichtmast uitgerust met een Outdoor Light Controller (OLC). De OLC is verantwoordelijk voor het aansturen van de verlichting en het versturen van de sensordata. Dit kan op twee manieren. Bij de eerste manier verstuurt de OLC de sensordata via RF (ZigBee) naar een Segment Controller (SC) in één van de lichtmasten. Deze kan vervolgens de gegevens van verschillende lichtmasten en sensoren bundelen en via 3G verzenden naar een server van de leverancier. Bij de tweede manier verstuurt de OLC de sensordata direct via LoRa naar de server. Hoe vaak de sensoren data versturen naar de centrale server moet afgesproken worden met de klant, vaker versturen betekent meer datakosten.

Vanaf de server van de leverancier is de data vervolgens toegankelijk voor de klant (gemeente) via het ALiS protocol. Dit protocol wordt sinds 2 jaar ontwikkeld door een groep leveranciers van openbare verlichtingssystemen in Nederland, in eerste instantie voor de bevordering van interoperabiliteit tussen leveranciers van systemen voor het centraal aansturen van openbare verlichting. Later is hier de mogelijkheid voor het ophalen van sensordata en het bekijken van de sensorstatus (logs) aan toegevoegd. Op dit moment is de standaardisatie door de ALiS foundation van de uitwisseling van sensordata gegenereerd door verschillende typen sensoren gaande.
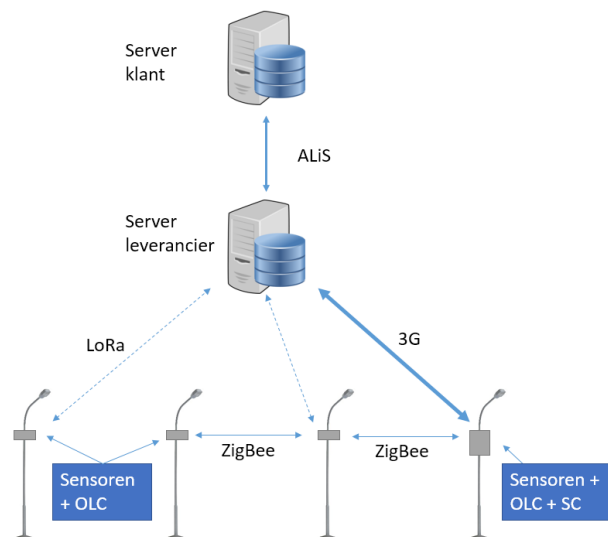
Figuur 1: Sensordata transport in Zichtenburg

Tijdens de pilot in Zichtenburg blijft de gegenereerde data op de server van de leverancier staan, ook nadat deze is opgevraagd door de gemeente. Later zouden hierover afspraken gemaakt moeten worden.

Een alternatief voor ALiS bestaat in de vorm van het TALQ protocol[1]. Dit protocol is al langer in ontwikkeling door een internationaal consortium en ondersteund meer functies, maar is gecompliceerder en de ontwikkeling gaat erg traag. Dit is de reden dat de Nederlandse leveranciers begonnen zijn met de ontwikkeling van ALiS.

De grote gemeenten, zoals Den Haag en Rotterdam, hebben voor het ontwikkelen van sensoren in de publieke ruimte een voorbeeldrol. Enerzijds omdat zij de middelen hebben om pilots zoals in Zichtenburg te starten en anderzijds omdat zij nog zelf het beheer voeren over de openbare verlichting.

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[1] http://www.talq-consortium.org/

B

Classification of area types

Table B.1 shows the classification of area types that is published by Statistics Netherlands every 3-4 years as *Bestand Bodemgebruik* [108].

Table B.1: Classification of area types by Statistics Netherlands

Category	Sub-category	Description
1. Traffic area		
	10	Railway area
	11	Road traffic area
	12	Airfields
2. Built-up area		
	20	Residential area
	21	Retail, hotel and catering area
	22	Area for public facilities
	23	Area for social or cultural facilities
	24	Business area
3. Semi built-up area		
	30	Dumping ground
	31	Scrapyard
	32	Cemetery
	33	Mining area
	34	Building site
	35	Others
4. Recreational area		
	40	Parks and gardens
	41	Sports area
	42	Allotment garden
	43	Single day recreational area
	44	Overnight recreational area
5. Agricultural area		
	50	Greenhouse area
	51	Other agricultural area
6. Forest and other natural areas		
	60	Forest
	61	Open dry natural area
	62	Wetlands
7. Inland waters		
	70	IJsselmeer/Markermeer
	71	Closed bay
	72	Rhine/Meuse
	73	Bordering lake
	74	Water reservoir
	75	Recreational waters
	76	Mining waters
	77	Flood-meadow
	78	Other internal waters
8. Coastal waters		
	80	Wadden Sea, Eems, Dollard
	81	Eastern Scheldt
	82	Western Scheldt
	83	North Sea
9. Foreign countries		
	90	Foreign countries

C
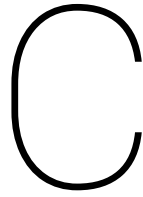
List of sensors types

This appendix shows a (non-comprehensive) list of 317 sensors, sensor types and classifications as given by [116]. The list is included in full to provide an overview and the selected sensor types to be deployed in the city of The Hague. The sensor types in bold have been selected for deployment in Smart City applications.

C.1. Acoustic, sound, vibration

- Geophone
- Hydrophone
- **Microphone**

C.2. Automotive, transportation

- Air flow meter
- Air–fuel ratio meter
- Blind spot monitor
- Crankshaft position sensor
- Curb feeler
- Defect detector
- Engine coolant temperature sensor
- Hall effect sensor
- Knock sensor
- Manifold Absolute Pressure sensor
- Mass flow sensor
- Oxygen sensor
- Parking sensors
- Radar gun

- Speedometer

- Speed sensor

- Throttle position sensor

- Tire-pressure monitoring sensor

- Torque sensor

- Transmission fluid temperature sensor

- Turbine speed sensor

- Variable reluctance sensor

- Vehicle speed sensor

- Water sensor

- Wheel speed sensor

C.3. Chemical

- Breathalyzer

- **Carbon dioxide sensor**

- Carbon monoxide detector

- Catalytic bead sensor

- Chemical field-effect transistor

- Chemiresistor

- Electrochemical gas sensor

- Electronic nose

- Electrolyte–insulator–semiconductor sensor

- Fluorescent chloride sensors

- Holographic sensor

- Hydrocarbon dew point analyzer

- Hydrogen sensor

- Hydrogen sulfide sensor

- Infrared point sensor

- Ion-selective electrode

- Nondispersive infrared sensor

- Microwave chemistry sensor

- Nitrogen oxide sensor

- Olfactometer

- Optode

- Oxygen sensor

- Ozone monitor

- Pellistor

- pH glass electrode

- Potentiometric sensor

- Redox electrode

- Smoke detector

- Zinc oxide nanorod sensor

C.4. Electric current, electric potential, magnetic, radio

- Current sensor

- Daly detector

- Electroscope

- Electron multiplier

- Faraday cup

- Galvanometer

- Hall effect sensor

- Hall probe

- Magnetic anomaly detector

- Magnetometer

- MEMS magnetic field sensor

- Metal detector

- Planar Hall sensor

- Radio direction finder

- Voltage detector

C.5. Flow, fluid velocity

- Air flow meter

- **Anemometer**

- Flow sensor

- Gas meter

- Mass flow sensor

- **Water meter**

C.6. Ionizing radiation, subatomic particles

- Cloud chamber

- Geiger counter

- Neutron detection

- Scintillation counter

C.7. Navigation instruments

- Air speed indicator

- Altimeter

- Attitude indicator

- Depth gauge

- Fluxgate compass

- Gyroscope

- Inertial navigation system

- Inertial reference unit

- Magnetic compass

- MHD sensor

- Ring laser gyroscope

- Turn coordinator

- TiaLinx sensor

- Variometer

- Vibrating structure gyroscope

- Yaw rate sensor

C.8. Position, angle, displacement, distance, speed, acceleration

- Auxanometer

- Capacitive displacement sensor

- Capacitive sensing

- Flex sensor

- Free fall sensor

- Gravimeter

- Gyroscopic sensor

- Impact sensor

- Inclinometer
- Integrated circuit piezoelectric sensor
- Laser rangefinder
- Laser surface velocimeter
- LIDAR
- Linear encoder
- Linear variable differential transformer (LVDT)
- Liquid capacitive inclinometers
- Odometer
- Photoelectric sensor
- Piezocapacitive sensor
- Piezoelectric accelerometer
- Position sensor
- Position sensitive device
- Rate sensor
- Rotary encoder
- Rotary variable differential transformer
- Selsyn
- Shock detector
- Shock data logger
- Stretch sensor
- Tilt sensor
- Tachometer
- Ultrasonic thickness gauge
- Variable reluctance sensor
- Velocity receiver

C.9. Optical, light, imaging, photon

- Charge-coupled device
- CMOS sensor
- Colorimeter
- Contact image sensor
- Electro-optical sensor
- Flame detector

- **Infra-red sensor**

- Kinetic inductance detector

- LED as light sensor

- Light-addressable potentiometric sensor

- Nichols radiometer

- Fiber optic sensors

- Optical position sensor

- Thermopile laser sensors

- Photodetector

- **Photodiode**

- Photomultiplier tubes

- Phototransistor

- Photoelectric sensor

- Photoionization detector

- Photomultiplier

- Photoresistor

- Photoswitch

- Phototube

- Scintillometer

- Shack-Hartmann

- Single-photon avalanche diode

- Superconducting nanowire single-photon detector

- Transition edge sensor

- Visible light photon counter

- Wavefront sensor

C.10. Pressure

- Barograph

- **Barometer**

- Boost gauge

- Bourdon gauge

- Hot filament ionization gauge

- Ionization gauge

- McLeod gauge

- Oscillating U-tube

- Permanent Downhole Gauge

- Piezometer

- Pirani gauge

- Pressure sensor

- Pressure gauge

- Tactile sensor

- Time pressure gauge

C.11. Force, density, level

- Bhangmeter

- Hydrometer

- Force gauge and Force Sensor

- **Level sensor**

- Load cell

- Magnetic level gauge

- Nuclear density gauge

- Piezocapactive pressure sensor

- Piezoelectric sensor

- Strain gauge

- Torque sensor

- Viscometer

C.12. Thermal, heat, temperature

- Bolometer

- Bimetallic strip

- Calorimeter

- Exhaust gas temperature gauge

- Flame detection

- Gardon gauge

- Golay cell

- Heat flux sensor

- Infrared thermometer

- Microbolometer

- Microwave radiometer

- Net radiometer

- Quartz thermometer

- Resistance temperature detector

- **Resistance thermometer**

- Silicon bandgap temperature sensor

- Special sensor microwave/imager

- Temperature gauge

- Thermistor

- Thermocouple

- Thermometer

- Pyrometer

C.13. Proximity, presence

- Alarm sensor

- **Doppler radar**

- **Motion detector**

- **Occupancy sensor**

- Proximity sensor

- **Passive infrared sensor**

- Reed switch

- Stud finder

- Triangulation sensor

- Touch switch

- Wired glove

C.14. Sensor technology

- Active pixel sensor

- Back-illuminated sensor

- Biochip

- Biosensor

- Capacitance probe

- Capacitance sensor

- Catadioptric sensor

- Carbon paste electrode

- Digital sensors

- Displacement receiver

- Electromechanical film

- Electro-optical sensor

- Fabry–Pérot interferometer

- Fisheries acoustics

- **Image sensor**

- Image sensor format

- Inductive sensor

- Intelligent sensor

- Lab-on-a-chip

- Leaf sensor

- Machine vision

- Microelectromechanical systems

- Photoelasticity

- Quantum sensor

- Ground-penetrating radar

- Synthetic aperture radar

- Radar tracker

- Stretch sensor

- Sensor array

- Sensor fusion

- Sensor grid

- Sensor node

- Soft sensor

- Sonar

- Staring array

- Ultrasonic sensor

- Video sensor

- Visual sensor network

- Wheatstone bridge

- Wireless sensor network

C.15. Other sensors and sensor related properties and concepts

- Actigraphy
- **Air pollution sensor**
- Analog image processing
- Atomic force microscopy
- Atomic Gravitational Wave Interferometric Sensor
- Attitude control (spacecraft): Horizon sensor, Earth sensor, Sun sensor
- Catadioptric sensor
- Chemoreceptor
- Compressive sensing
- Cryogenic particle detectors
- Dew warning
- Diffusion tensor imaging
- Digital holography
- Electronic tongue
- Fine Guidance Sensor
- Flat panel detector
- Functional magnetic resonance imaging
- Glass break detector
- Heartbeat sensor
- Hyperspectral sensors
- Interferometric Reflectance Imaging Sensor (IRIS)
- Laser beam profiler
- Littoral Airborne Sensor/Hyperspectral
- LORROS
- Millimeter wave scanner
- Magnetic resonance imaging
- Moire deflectometry
- Molecular sensor
- Nanosensor
- Nano-tetherball sensor
- Omnidirectional camera
- Organoleptic sensors
- Optical coherence tomography

- Phase unwrapping techniques

- Polygraph Truth Detection

- Positron emission tomography

- Push broom scanner

- Quantization (signal processing)

- Range imaging

- Scanning SQUID microscope

- Single-Photon Emission Computed Tomography (SPECT)

- Smart dust

- Superconducting Quantum Interference Device (SQUID)

- Special Sensors-Ions, Electrons, and Scintillation thermal plasma analysis package (SSIES)

- Special Sensor Microwave Imager Sounder (SSMIS)

- Structured-light 3D scanner

- Sun sensor, Attitude control (spacecraft)

- Superconducting nanowire single-photon detector

- Thin-film thickness monitor

- Time-of-flight camera

- Triangulation and LIDAR Automated Rendezvous and Docking (TriDAR)

- Unattended Ground Sensors

D
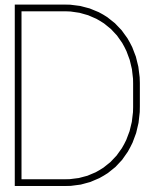
Rijksdriehoeks-coordinates

The Rijksdriehoeks-coordinate system (EPSG:28992) is a coordinate system used primarily by the Dutch government and public institutions in The Netherlands. It was originally defined by using the city of Amersfoort as the point of intersection between the x and y axis of the system, but this has been changed for practical reasons. In the current system, all values of x and y coordinates of points within the European part of The Netherlands are positive, while the y coordinate is always larger than the x coordinate within this scope. The current coordinate system is displayed in figure D.1 [54], showing the origin now to be somewhere in northern France.

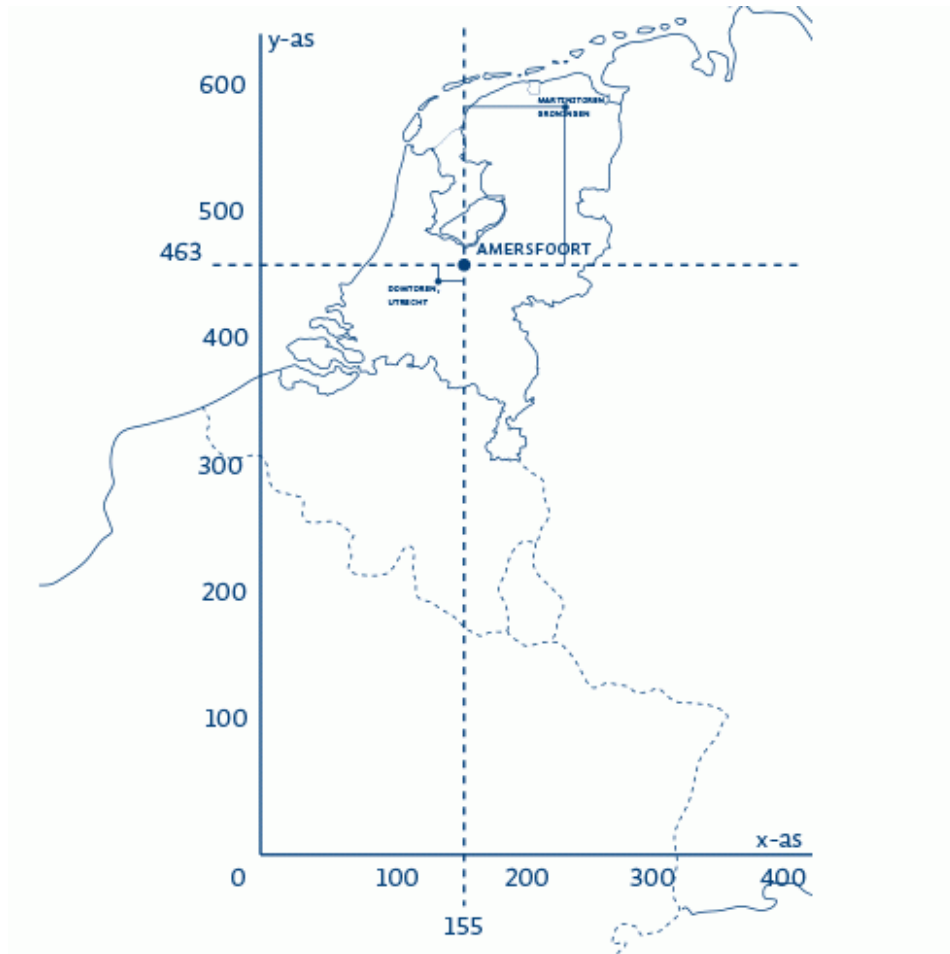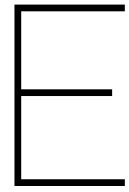Figure D.1: The Rijksdriehoeks-coordinate system

E

Entity-relationship diagram

The different entities serving in the cost optimisation model described in chapter 4 have certain properties and relations to each other. This can be shown graphically in a so-called entity-relationship diagram. Figure E.1 shows this diagram for all entities involved in the implementation of the cost optimisation model.

Figure E.1: Entity-relationship diagram

PublicSpaceEntity
- Name
- Type
- X
- Y
- Radius

PhysObject
- Type
- Municipality
- Neighborhood
- X
- Y
- Z

ObjectType
- Name
- Powered

Mount
- Sensor
- Object

Sensor
- Type
- Mount
- Connection
- IsSink

SensorType
- Name
- Quantity
- ObjectType
- AverageFrequency
- MaximumFrequency
- MinimumFrequency
- MaximumLatency
- MeasurementDataSize
- ExpectedLifetime
- Rules

Connection
- Type
- Sensor
- AccessPoint
- Distance

ConnectionType
- Name
- Type
- Subtype
- MaximumThroughput
- MinimumLatency
- MaximumDistance
- Capex
- CapexAccount
- CapexDistance
- CapexClasses
- CapexWriteOff
- Opex
- OpexType
- OpexAccount
- OpexMonth
- OpexData
- PricePlans

AccessPoint
- Name
- Type
- SupportsConnectionType
- X
- Y
- Z

F
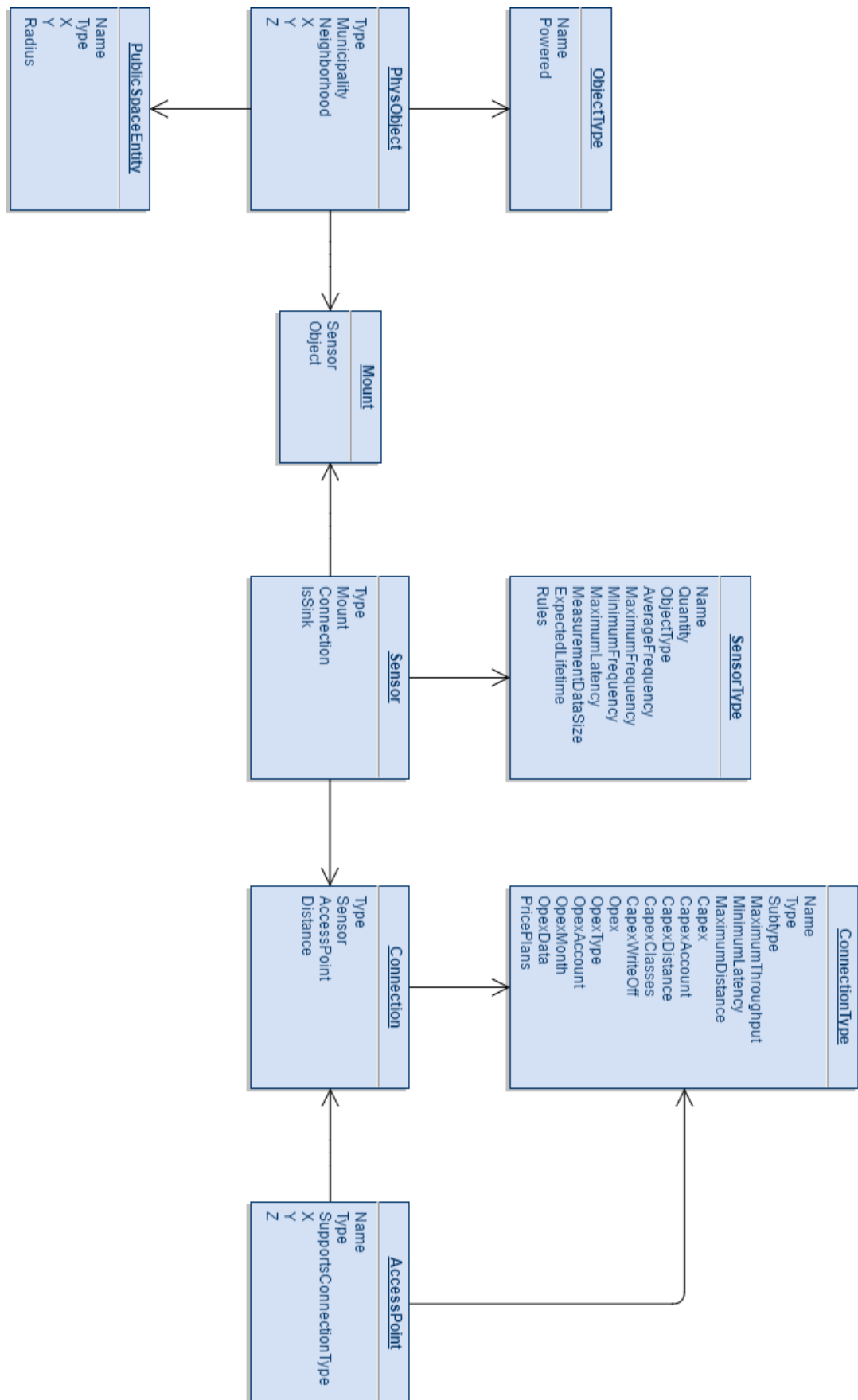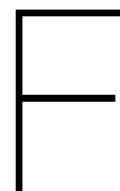
Model parameters

This appendix gives an overview of the cost-optimisation parameters available during simulation. Values of the parameters that have been used during the simulations are shown where available. Values marked as [CONF] have been supplied by KPN for the purpose of this research but cannot be made public due to a confidentiality agreement.

F.1. Link modelling parameters

Table F.1: Link modelling parameters

Parameter	KPN value	Unit	Description
DSL_MONTH	[CONF]	€/month	DSL monthly subscription cost price
DSL_WRITE_OFF	[CONF]	years	Write off period of newly added lines investment cost
DSL_NEW_LINE	[CONF]	€	DSL new line investment cost (distance below 25 meter)
	[CONF]	€	DSL new line investment cost (distance 25-50 meter)
	[CONF]	€	DSL new line investment cost (distance 50-75 meter)
	[CONF]	€	DSL new line investment cost (distance 75-100 meter)
	[CONF]	€	DSL new line investment cost (distance 100-125 meter)
FIBRE_MONTH	[CONF]	€/month	Fibre monthly subscription cost price
FIBRE_WRITE_OFF	[CONF]	years	Write off period of newly added lines investment cost
FIBRE_NEW_LINE_BASE	[CONF]	€	Fibre new line investment cost (distance below 100 meter)

Parameter	KPN value	Unit	Description
FIBRE_NEW_LINE_ADD	[CONF]	€/meter	Additional fibre new line investment cost (distance 100-250 meter)
	[CONF]	€/meter	Additional fibre new line investment cost (distance 250-500 meter)
	[CONF]	€/meter	Additional fibre new line investment cost (distance 500-1000 meter)
LORAWAN_MONTH	[CONF]	€	LoRaWAN yearly subscription cost price per device (exact value depending on the total number of messages)
LORAWAN_MESSAGE_UP	[CONF]	€/message	LoRaWAN uplink message price (exact value depending on the total number of messages)
LORAWAN_MESSAGE_DOWN	[CONF]	€/message	LoRaWAN downlink message price (exact value depending on the total number of messages)
LTE_GB	[CONF]	€/GB	LTE data cost price per GB
LTE_MONTH	[CONF]	€/month	LTE monthly subscription cost price
ZIGBEE_NODE	[CONF]	€	ZigBee new node

F.2. Parameters related to the selected sensor types

Table F.2: Sensor selection parameters

Parameter	Unit	Description
n		Number of included sensor types in the simulation
N_i		Number of included sensors of type i
D_i	Byte	Data production per measurement of sensor type i
f_i	Hz	Measurement frequency of sensor type i

F.3. Parameters related to the public space model

Table F.3: Public space model parameters

Parameter	The Hague value	Unit	Description
α	1.5		Parameter to control the relative size of crossroad model surface compared to the actual surface of the crossroad
β	$\frac{1}{3}$		Parameter to control the relative size of the road model surface compared to the actual surface of the road

List of abbreviations

2G	Second Generation mobile network
3G	Third Generation mobile network
3GPP	The 3rd Generation Partnership Project
4G	Fourth Generation mobile network
ADSL	Asynchronous Digital Subscriber Line
API	Application Programming Interface
BGT	Basisregistratie Grootschalige Topografie
BVVDSL	Bonded Vectored Very-high-bit-rate Digital Subscriber Line
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
CDMA	Code division multiple access
DRIP	Dynamisch Route-informatiepaneel (Dynamical route information panel)
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
FttH	Fibre-to-the-Home
FttO	Fibre-to-the-Office
GIS	Geographical Information System
ICT	Information and Communication Technology
IoT	Internet of Things
ITS	Intelligent Transport Systems
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
KANVAS	Kabel Ader Netwerk Verbinding Adresregistratie Systeem
LAN	Local Area Network
LoRa	Long Range
LPWAN	Low-Power Wide-Area Network
LTE	Long Term Evolution
M2M	Machine-to-Machine
MRDH	Metropoolregio Rotterdam Den Haag (Metropolitan area Rotterdam The Hague)
ORAC	Ondergrondse RestAfval Container (Underground garbage container)
PSTN	Public Switched Telephone Network

RD-coordinates   Rijksdriehoekscoordinaten (A coordinates system used in The Netherlands by govern-
                        ment publications

TCP/IP   Transmission Control Protocol/Internet Protocol

VDSL   Very-high-bit-rate Digital Subscriber Line

VRI   Verkeersregelinstallatie (Set of traffic lights)

WAN   Wide Area Network

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