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Cost model for a 5G smart light pole network

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Cost model for a 5G smart light pole network

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Abstract of the master's thesis

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Abstract

To overcome the future lack of mobile broadband capacity in urban, densely populated areas, the deployment of fifth-generation (5G) cellular network base stations on light poles has been considered. The resulting smart light poles can accelerate the advent of new smart city services. The connectivity provided by light poles enables a platform for connected devices. These devices can be cameras, sensors and even electric vehicle charging stations. A platform based on connected smart light poles meets the need of a smart city.

This thesis proposes a generic cost model to quantify and analyze the total deployment costs (TDC) of a smart light pole deployment project. Four different pole configurations and a grid-based deployment structure that assigns poles to zones with different service demands are introduced to meet the various requirements of a smart city. Furthermore, we estimated future costs by developing a cost evolution module. Cost distribution functions were applied and Monte Carlo simulations performed to cover variations and uncertainties in the deployment process.

The cost model was tested by assuming two different deployment scenarios. Results show that the total deployment costs in a ten square kilometer area will be around 6.57 M€/km^2 for massive service deployment and 4.84 M€/km^2 for minimum deployment providing uniform coverage of basic services. These values can potentially decrease to 3.23 M€/km^2 and 4.05 M€/km^2 when cost evolution is considered. Although more than 30% cost reduction might be possible, this is mainly caused by the improvement of prototype components, given that public works are less sensible to cost evolution. Therefore, we recommend cities to promptly start civil works and to select upgrade-able pole designs. The costs components that have the highest share on the overall costs are the 5G small cell base station and the pole shaft. These results will help the smart city enabling stakeholders to plan their investments and furthermore shows them the key cost aspects.

Keywords Cost modelling, 5G, Small Cell, Smart Cities

Preface

I would like to thank and express my gratitude towards Professor Heikki Hämmäinen and my advisor Jaume Benseny Quintana.

Heikki's support and guidance for my thesis and research work has resulted in a great experience and learning during the master thesis tenure. His vision and ways of teaching has helped me to understand and think about the bigger picture in my thesis work and to understand valuable aspects related to business and management of upcoming communication technologies. His guidance assisted me infinitely while researching and writing this thesis.

Jaume Benseny Quintana is a great critic, and his advice has supported me a lot during my thesis writing. I would like to express thanks to the Network Business research team members for their help and knowledgeable comments.

Furthermore, I want to thank all the friends I found during my time in Finland, especially Nathan Atta for all their support, entertainment, and kindness. I would not have been able to work on this thesis in Finland without the great support from Professor Erich Leitgeb from the Graz University of Technology.

Finally, I would like to thank my parents and sister for their infinite love and help throughout my studies at the University of Aalto, Finland. To them, I dedicate this thesis.

Otaniemi, 31.8.2018

Oliver Landertshamer

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Abbreviations and Acronyms

4G	Fourth Generation
5G	Fifth Generation
AoI	Area of Interest
BS	Base Station
CAPEX	Capital Expenditure
CRU	Common Radome Unit
eMBB	Enhanced Mobile Broadband
EV	Electric Vehicle
FC	Full Configuration
GHG	Greenhouse Gas
GHz	Gigahertz
IoT	Internet of Things
L5G	Light + 5G
L5GS	Light + 5G + Sensors
LED	Light Emitting Diode
LO	Light Only
LOS	Line of Sight
M2M	Machine-to-Machine
MC	Macro Cell
MCS	Monte Carlo Simulation
MHz	Megahertz
mMTC	Massive Machine Type Communication
mmW	Millimeter Wave
MNO	Mobile Network Operator
NHO	Neutral Host Operator
NLOS	Non-Line of Sight
OPEX	Operational Expenditure
PDF	Probability Density Function
PERT	Program Evaluation and Review Technique
RA	Risk Analysis
RAN	Radio Access Network
RAT	Radio Access Technology
RTK	Real-Time Kinematic
SC	Small Cell
TDC	Total Deployment Costs
URLLC	Ultra-Reliable Low Latency Communication
WiGig	Wireless Gigabit

1 Introduction

This section introduces the background and context of the thesis, motivates the research from technology and business perspectives, defines the research question, and presents the structure of the thesis.

This thesis and the thereby developed cost model is part of the Nokia Bell Labs driven project *LuxTurrim5G*, funded by Business Finland, with the goal to build key enablers for fast 5G network based on smart light poles, which will form the digital backbone of future smart cities.

1.1 Motivation

The increasing level of urbanization worldwide established a necessity for coping with the challenges that go along with it. A new level of infrastructure services, energy efficiency, air quality, effectivity of transportation and quality of living are some of the aspects that need to get improved. Therefore, along with the evolution and rise telecommunication technologies the term smart city was formed. The growing need for a new generation service infrastructure to provide new digital ecosystems in those smart cities are currently facing some problems. One of those is the insufficiency of mobile network capacity due to the increasing number of users and new digital services. This bottleneck threatens the realizations of smart cities. This problem can be solved by using 5G small cell (SC) technology that operates in higher radio frequencies than current mobile network systems. This new technology requires a dense network of antennas and therefore setting new requirements for base station deployment. The *LuxTurrim5G* project is tackling that problem by developing comprehensive technical solutions, services and infrastructure for smart light pole based 5G networks to create an ecosystem solving the critical challenges of future smart cities.

The smart light pole approach is feasible due to the necessity of street lightning in every city. Street lighting is an important public service that provides security to all kinds of traffic participants, but it is also a cost drain. The cost of purchasing, installing, powering and maintaining street lighting is an annual cost point in a city's balance. This annual cost could be avoided if a casual lamppost is upgraded to a so-called smart light pole that, in addition to illuminating the street, generates income by facilitating services and applications based on the principles of the Internet of Things (IoT).

Another important driver is the development of a 5G data network and the need for a large number of small cells due to the requirements of millimeter-wave (mmW) 5G technology. Increasing the number of 5G SCs comes with several challenges including finding unobtrusive deployment sites, getting the approvals for the installation from property owners and providing backhaul connections leading to the core network. A comprehensive solution for the aforetime mentioned challenges would be the installation of 5G SCs on many smart light poles.

Moreover, there is a need for unobtrusive electric vehicle (EV) charging points for EV drivers without a driveway or garage. This need will greatly increase due to the transition to electric mobility [1]. In cities and municipalities, the percentage of homes having access to a garage is around 30%, this means 7 out of 10 electric car owners will not be able to recharge their car at their home. The aim is to provide charging points at locations where the car is parked in the public domain. For aesthetic reasons, and to avoid the lack of charging stations, charging points will be implemented in the smart light poles. Pilot projects are already running in Canada [2].

Furthermore, the annual cost of conventional equipped public street lighting is assumed to be approximately 100€ per light point [3]. Even though switching to LEDs offers great savings on energy consumption and maintenance costs, it is still an annual recurring cost. Therefore, the prospect of facilitating new applications and services, each generating a steady stream of recurring income, is very much welcomed for cities and municipalities.

Nevertheless, a city-wide smart light pole deployment is a complex and costly venture and it is a complicated task to figure out how to build revenue streams from the provided services. There are already many uncertainties that have to be taken into account when it comes to the deployment of smart light poles. Additional digging and excavation work has to be done to provide these poles with more power and connectivity. Therefore, we developed a cost model to analyze the associated smart light pole deployment costs.

1.2 Research Question

To understand and forecast the costs related to the 5G smart light pole deployment we address the following research questions:

- What is the total deployment cost (TDC) for a 5G smart light pole network in an urban environment?

- What are the key cost aspects in the structure and deployment of 5G light poles?

As the research questions indicates, the core challenges are the gathering of the relevant cost data and to build up a model that associates all kinds of parameters to make a realistically estimation of the total deployment costs for a citywide smart light pole network.

1.3 Scope of Research

The scope of the research includes future 5G smart light pole deployment costs by setting up a spreadsheet based model to identify the key cost aspects as well as the TDC including a long term cost forecast. There is still an uncertainty about the (future) ownership of the whole smart light pole infrastructure. Many different ownership scenarios are possible e.g. mobile network operators (MNOs), power supply companies, the cities themselves or even a neutral host operator (NHO) [4]. By focusing on TDC, we are including capital and operational expenses. These results will help the smart city enabling stakeholders to plan their investments and furthermore shows them the key cost aspects.

1.4 Research Methods

The research methods used in the thesis are cost modelling focusing on TDC. Due to numerous uncertainties regarding the future deployment and ownership of smart light poles, we furthermore considered quantitative risk analysis (RA) and Monte Carlo simulation (MCS) as a method to estimate several parameters e.g. SC coverage, specific sensor installation and cost evolution.

We interviewed experts from Finnish cities, network equipment vendors, MNOs, as well as small and medium enterprises, who have been involved in the *LuxTurrim5G* project. Moreover, attendances at workshops and conferences also supplemented this thesis. Thus, the research approach is a mix of qualitative and quantitative methods. To answer the research question, we gathered cost data from pilot areas, studied city guidelines and 5G mmW technology. It is a complex task to identify and forecast the possible future deployment scenarios. Therefore, we used statistical methods to cover uncertainties and lack of knowledge.

We introduce two deployment scenarios. In scenario one, we assume a coverage only case in which the main objective is to enable seamless SC coverage via smart light poles with very few sensors and in scenario two we consider a heavy sensor and 5G SC deployment to enable massive data gathering and mobile network capacity. This methods allowed us to get probability density functions (PDFs) as results that provides an estimation of the total cost range.

1.5 Structure of the Thesis

After introducing the topic, motivation, research question and methods in Chapter 1, the rest of the thesis is structured as followed.

Chapter 2 shows the literature review on smart cities, 5G millimeter wave technology and its deployment to provide information about the background and ongoing projects. Furthermore it is providing information about previous work on cost modelling of small cells and infrastructure deployment as well as risk analysis and Monte Carlo simulation for project planning.

In Chapter 3, the cost model for the smart 5G light pole deployment is explained. It gives an overview of the three main cost model modules and the resulting total today's and future deployment costs calculation. It presents in detail how we calculated the main parameters and our assumptions regarding the future cost evolution.

In Chapter 4 we evaluate the cost model for a minimum deployment scenario and a massive deployment scenario. We explain the grid-based pole alignment approach which is the basis for most of the following calculations.

Chapter 5 presents the results of the performed Monte Carlo simulation. We do this by showing a summary of the main simulation input parameters, followed by the three main results. These are the probability distributions of the total deployment costs, the effects of cost evolution and the relative contribution of individual cost items.

Chapter 6 concludes the thesis by evaluating, assessing and exploiting the results. Furthermore, we give an outlook to the future research in this field.

2 Literature Review

The main long term goal of the smart light pole deployment is to enable so-called smart cities. Smart city is a concept with a very wide range of applications to interconnect several actors from industry, public and government. Furthermore, a network of smart light poles with its several sensors can help improve the environment by tracking air quality status and traffic flow control.

2.1 Smart Cities

As the term “smart city” gains wider and wider currency, there is still confusion about what a smart city is, especially since several similar terms are often used interchangeably [5]. The concept of smart growth was largely used in the 1990s within the framework of new urbanism, as a community-driven reaction to worsening trends in traffic congestion, school overcrowding, air pollution, loss of open space, effacement of valued historic places, and skyrocketing public facility costs [6]. In Europe, 75 percent of the population already lives in urban areas and the number is expected to reach 80 percent by 2020. The importance of urban areas as a global phenomenon is confirmed by the diffusion of mega cities of more than 20 million people in Asia, Latin America, and Africa [7]. As a result, nowadays most resources are consumed in cities worldwide, contributing to their economic importance, but also to their poor environmental performance. Cities consume between 60 percent and 80 percent of energy worldwide and are responsible for large shares of greenhouse gas (GHG) emissions [7]. However, the lower the urban density, the more energy is consumed for electricity and transportation, as proved by the fact that CO2 emissions per capita drop with the increase of urban areas density [8].

Vito et al. [5] did research on the the different definitions and initiatives of smart cities. They tried to clarify the smart city concept and provided an in-depth literature analysis. Their conclusion shows the difficulty of a universal smart city definition due to the variety of characteristics of cities worldwide. The authors recommend that every city need its own smart city framework to asses its particular vision. Nevertheless, some key aspects relate to all smart city concepts. Lombardi et al.[9] have identified six components with aspects of urban life, as shown in Table 1.

Table 1: Components of a smart city and related aspects [9]

Components of a smart city	Related aspect of urban life
smart economy	industry
smart people	education
smart governance	e-democracy
smart mobility	logistics & infrastructure
smart environment	efficiency & sustainability
smart living	security & quality

2.2 5G Millimeter-Wave Mobile Broadband Deployment

The fifth-generation networks foreseen to markedly outperform legacy mobile systems are set to launch around the year 2020. The 5G networks (also known as IMT-2020) are anticipated to support three broad categories of use cases, namely: enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (URLLC) and massive machine type communications (mMTC) [10]. A judicious combination across all bands is likely to be important for 5G. This could include: lower frequencies for wide area coverage, high rate mmW links for local and personal area communications, and short range indoor links in the unlicensed spectrum range of the mm-wave bands [11]. Mobile networks must meet new demands as human communications changes from click and wait/background traffic, to interactive, real-time, haptic communication, and introduction of critical machine-to-machine (M2M) type communications. The networks must provide significantly reduced end-to-end latency and higher reliability than is achievable today. Ultra-reliability is vital for safety. Low latency is crucial to ensure applications are usable and interactive whether human-to-human, human-to-machine or machine-to-machine communication [12]. Figure 1 gives an overview of the services and use cases enabled by 5G mobile broadband technology.

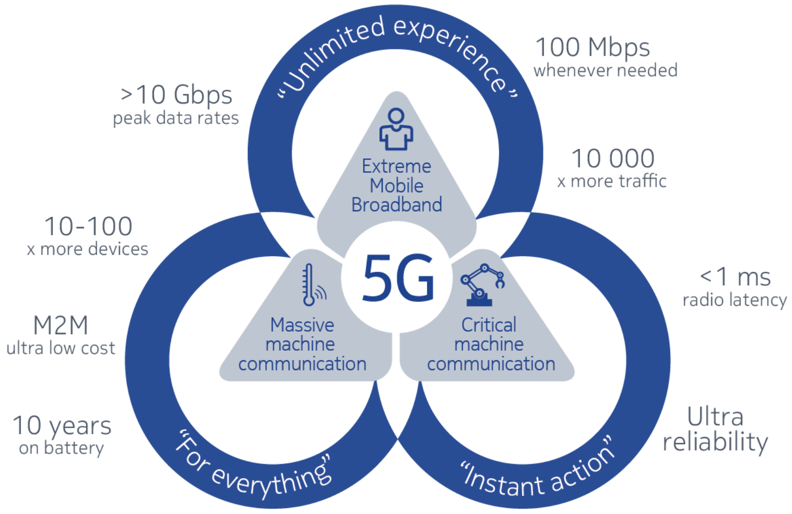

Figure 1: 5G Diversity of service, use case and requirements [12]

Current 4G macro cells (MCs) can cover a wide area due to the good propagation properties of the 600 MHz to 2600 MHz frequencies. A cost efficient way to enable 5G is the upgrade of current 4G MCs. The downside of MCs frequency bands is its limiting the mobile broadband capacity. Busari et al. [13] simulation results present an average MC capacity of 40 Mb/s. This will not be enough to cover the rapid increase of mobile data growth, mainly due to heavy smart phone usage. Therefore, the millimeter wave frequency spectrum needs to get utilized in order to increase the usable bandwidth. The most promising carrier frequency is between 28 and 37 GHz which will enable bandwidths up to 1 GHz. In this case, a very dense deployment of so-called millimeter wave small cells will be necessary to overcome the limited propagation properties of this high frequency. Depending on the area, the SCs are capable of transmitting to a distance up to 200 meters in line of sight (LOS) cases. In a non-line of sight (NLOS) case, the range is limited to roughly 75 meters due to fading caused by reflections, diffraction, scattering and shadowing on buildings and other urban obstacles.

Furthermore, [13] concludes that for ultra dense networks, the SCs will be deployed based on the 50-200 m intersite distance and the optimal cell density threshold of the network. The multi-GHz contiguous bandwidth in the 30-300 GHz mmWave spectrum and the 0.1-10 THz bands will support multi-gigabits-per-second (Gb/s) data rates. At 70 GHz, for example, the number of antenna elements can go up to 1024 at the base station (BS) and 64 at the user equipment, according to 3GPP, thereby realizing massive MIMO.

Nevertheless, mmW - SCs that are deployed outdoors, as they are in the smart light pole case, will not be able to provide sufficient indoor mobile data throughput due to high wall and indoor losses. New window designs and materials are currently investigated to decrease these losses to make the outdoor SCs beneficial for indoor users. To provide a beneficial increase in mobile broadband capacity and subsequently throughput, a cooperating network of macro and small cells has to be established. Busari et al. [13] proposes a two-tier architecture as presented in Figure 2 where the μwave BSs provide coverage and signaling for the MCs while the mmW SCs serve as hotspots for users with high data rate demands, broadband or bandwidth-hungry applications.

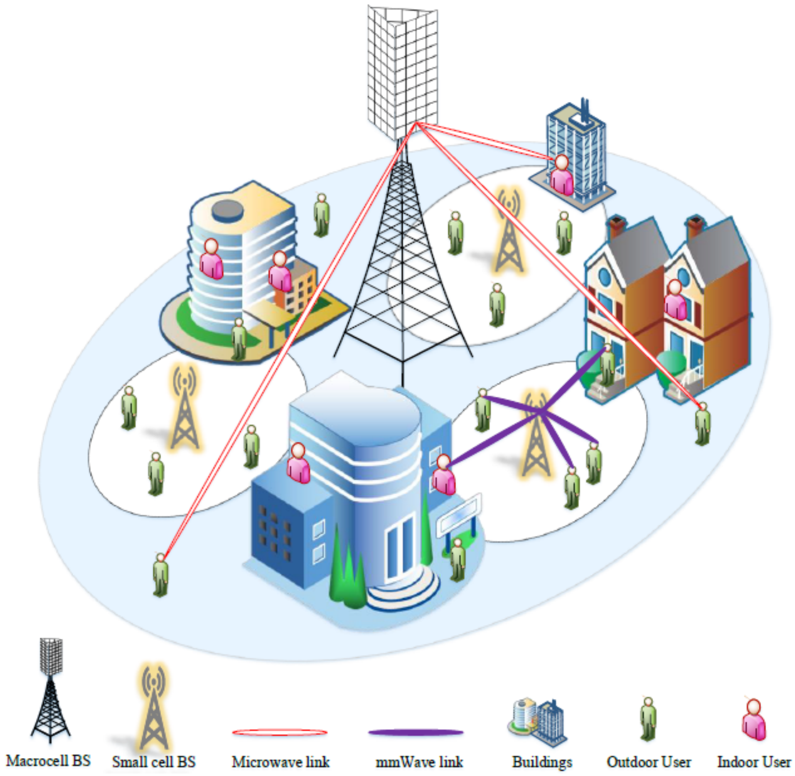

Figure 2: 5G two-tier network layout [13]

2.3 Cost Modelling

Although there are already several papers on cost models [14], [15], [16], [17] and techno-economic analyses [18] of 4G and 5G deployment, there is lack of publications for smart 5G light poles. [19] provides a detailed cost analysis for smart lighting solutions. However, it does not take different pole configurations into account, which is the main advantage of our cost model. Cost modelling is an approach that allows one to compare the differences between data traffic demand and network costs for different deployment scenarios. Katsigiannis & Smura [14] and Nikolikj & Janevski [16] have begun to integrate mmW bands spectrum into cost modelling heterogeneous networks whereby small cell solutions such as pico cells with mmW systems are deployed in areas of high demand [16]. The cost modelling approach used in this work is based on the work of Katsigiannis and Smura where they identified the cost structure of radio access networks and explicitly models the network costs as a function of data traffic, both in the short-run (current network) and in the long-run (future capacity expansion scenarios). In their work, they focused on answering the question: "What does a mobile operator need to produce data traffic?" to identify the main cost factors and furthermore clasify them to CAPEX and OPEX. The main target of this thesis is to identify the total deployment costs of 5G smart light pole deployment in an urban area. Nevertheless, the techno-economic model proposed by [20] was used to start identifying the input parameters related to the service, the market and the technology. Furthermore, the work of Nikolikj & Janevski was used as a guideline for the mmW coverage and cost scenarios in this thesis. The cost modelling starts with an elaboration of radio access network (RAN) specific coverage, capacity and unit cost estimates for various BS classes deployed with advanced radio access technologies (RATs). The next step is investment modelling of various wireless network deployment scenarios.

2.4 Risk analysis and Monte Carlo Simulation

The main objective of risk analysis is to establish a rational foundation for objective decision making. The risk analysis aims at quantifying the undesirable effects that a given activity may impose on humans, the environment or economical values. The objective of the decision process is then to identify the solution that in some sense minimizes the risk of the considered activity [21].

A complete risk assessment procedure is likely to consist of five steps [22]:

1. Identification of the risk that is to be analyzed
2. A qualitative description of the problem and the risk – why it might occur, what you can do to reduce the risk, probability of the occurrence etc.
3. A quantitative analysis of the risk and the associated risk management options that is available to determine or find an optimal strategy for controlling and hereby solving the risk problem

4. Implementing the approved risk management strategy
5. Communicating the decision and its basis to various decision-makers.

The quantitative nature of the proposed cost model, allows us to use distribution functions to cover some of the uncertainties and the lack of knowledge. These quantitative risk analysis approach is performed by combining distribution functions with MCS which allows us to add up the variations of distribution values independently. These variations are often referred to as "what if" scenarios where the advantage of using quantitative risk analysis is that instead of only creating a number of possible scenarios, it effectively accounts for every possible value that each variable within the model can take by use of various continuous probability distributions. Each variable/parameter assigned a probability distribution result in different scenarios that are weight together by the probability of occurrence [23].

According to [23] the Monte Carlo method is now one of the most powerful and commonly used techniques for analyzing complex problems. The different types of applications can be found in many fields from radiation transport to river basin modeling. Furthermore, it is not only on stochastic processes the MCS is applicable, but also at deterministic problems this method is usable.

Three major points suggesting a Monte Carlo method instead of traditional simulation methods:

1. In the Monte Carlo method time does not play as substantial role as it does in stochastic simulation in general
2. The observations in the Monte Carlo method, as a rule, are independent. In simulation, however, the experiment with the observations is over time so, as a rule, these are serially correlated and hence dependent of each other.
3. In the Monte Carlo method it is possible to express the responses in a rather straightforward manor by simple functions of the stochastic input variables. In simulation the response is often a very complicated one and can only be expressed explicitly by computer programs.

In order to asses the uncertainties of some parameters a suitable distribution function had to be chosen. The framework shown in Figure 3 was used to decide which distribution function should be used in the cost model.

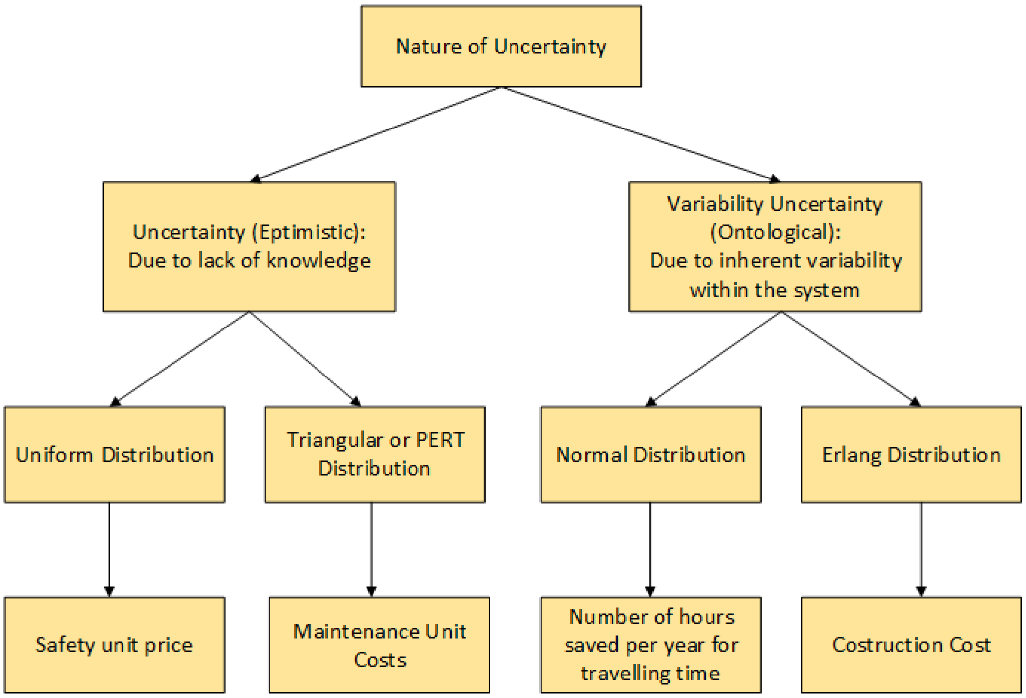

Figure 3: Overview of applied uncertain impacts within the risk analysis framework [23]

Due to fact that we are dealing with electronic equipment that is either already on the market or at least in prototype stage and moreover gathered in formations from industry expert interviews, we got specific cost data or at least actual cost indicators that allows us to set a minimum and maximum cost range. Therefore we decided to use Beta-PERT distribution (from here on just referred to as the PERT distribution) for the cost model.

PERT stands for Program Evaluation and Review Technique and got introduced as a schedule planning method for large and complex projects developed by the US Navy in the 1950s. The PERT is derived from the Beta distribution and covers a huge variety of types of skewness. When used in a Monte Carlo simulation, the PERT distribution can be used to identify risks in project [23]. Like the triangular distribution, the PERT distribution emphasizes the "most likely" value over the minimum and maximum estimates, which limits the usefulness by the quality of inputs. The PERT distribution constructs a smooth curve which places progressively more emphasis on values around (near) the most likely value, in favor of values around the edges. In practice, this means that we "trust" the estimate for the most likely value, and we believe that even if it is not exactly accurate (as estimates seldom are), we have an expectation that the resulting value will be close to that estimate [23].
Figure 4 shows the comparison of the triangular and PERT distribution.

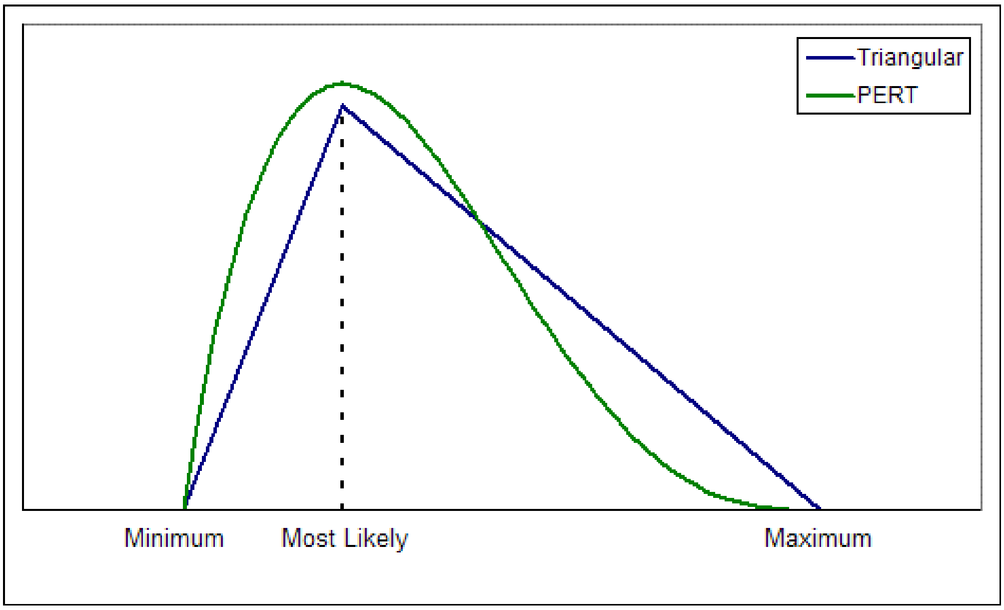

Figure 4: Illustration of the triangular distribution vs. PERT distribution [22]

The formulas to calculate the mean μ of the triangular and PERT distribution, as well as the PERT variance of a PERT distribution are as followed:

$$\mu_{Triangular} = \frac{min + mode + max}{3} \tag{1}$$

$$\mu_{PERT} = \frac{min + 4 \cdot mode + max}{6} \tag{2}$$

$$var_{PERT} = (\frac{max - min}{6})^2 \tag{3}$$

The Formulas show that in real-life problems we are more confident in the "most likely" mode value estimate, therefore the four time weighting on the mode. For our purposes of project cost, it has a satisfying smooth shape, as opposed to the unnatural angular shape of the triangular distribution.

3 Cost Model Definition

3.1 Cost Model Structure

The cost model proposed calculates the total costs of a smart light pole deployment in an urban environment. It furthermore estimates the future TDC as a function of deployment parameters and the evolution of key cost items. The model is separated in three modules:

1. *Pole Configuration Module:*

   It defines four different smart pole configurations to satisfy the demands of a smart city. Each configuration includes a different set of hardware components to allow multiple sensor combinations.

2. *Infrastructure Module:*

   It estimates capital and operational expenses for the deployment of the pole network. We calculate the total number of necessary poles in each configuration.

3. *Cost Evolution Module:*

   It estimates future cost values for pole configurations and infrastructure considering prototype improvement, volume sale discounts, and price erosion.

By combining these three modules, the model is able to calculate the today's and future total deployment costs. An overview of the TDC calculation process is presented in Figure 5. The processing of the costs data is are generic and applicable independent of the geographical area and/or city size. Every parameter in the model can be modified so that is suits a different city's requirement.

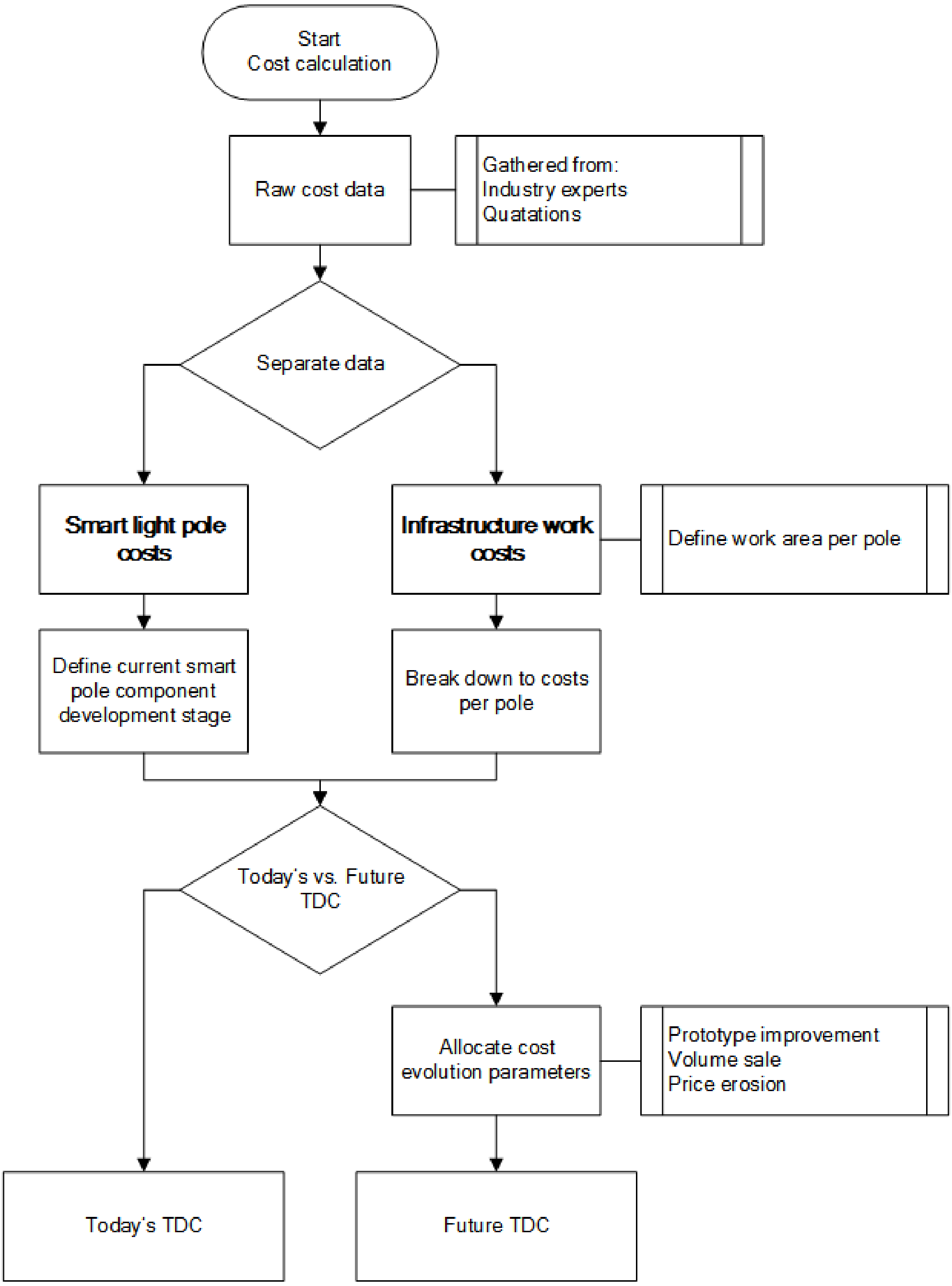

Figure 5: Workflow to calculate the current and estimated future costs of smart light pole deployment components

3.2 Pole Configuration Module

We define four configurations, each of which contains a different set of hardware components.

- **Light Only (LO)**
  Smart light pole that provides smart lighting using LED technology.
- **Light + 5G (L5G)**
  Provides additional mobile network connectivity via 28 GHz small cell base station installed inside a radome unit.
- **Light + 5G + Sensors (L5GS)**
  Additionally provides sensor coverage including video surveillance, weather and air quality monitoring, sound sensing and audio reproduction, and RTK positioning.
- **Full Configuration (FC)**
  Provides complete smart city functionality by additionally supporting high quality video surveillance, EV charging, and information displays.

Table 2: Pole Configurations

	Prototype (P) / Market (M)	**LO**	**L5G**	**L5GS**	**FC**
Pole shaft	M	x	x	x	x
Pole base	M	x	x	x	x
Utility box	P	x	x	x	x
Common radome unit	P		x	x	x
Smart lights	M	x	x	x	x
Weather & air quality sensor	M			x	x
External camera system	M				x
Integrated camera system	M			x	x
Sound sensing & speaker	M			x	x
External information display	P				x
RTK positioning	P			x	x
EV charger	M				x
Drone station	P				x
28 GHz 5G base station	P		x	x	x
Today's cost		**7 000 €**	**15 000 €**	**31 000 €**	**60 000 €**
Future minimum cost estimate		**4 500 €**	**8 000 €**	**20 000 €**	**34 000 €**

3.3 Infrastructure Module

We estimate the capital and operational expenses to conduct a greenfield deployment that satisfies the coverage requirements from different pole components. The model assumes fiber-based backhaul since civil works are anyway conducted due to greenfield deployment.

3.3.1 Total number of poles $\mathbf{P_{total}}$

In order to calculate the deployment costs we have to calculate the amount of poles $\mathbf{P_{total}}$ in the area we want to observe. Given the full size of the area to be covered $\mathbf{A}$, we furthermore introduce the parameter area of interest (AoI) $\mathbf{p_{AoI}}$ which represents the percentage of the overall area where a smart light pole deployment is desired and possible (e.g. no woods, lakes or agriculture fields). The AoI parameter allows us to modify the number of poles based on the geographical conditions. We considered a rectangular grid-like pole deployment with a pole-to-pole distance $\mathbf{d_{ptp}}$ according to the corresponding city guideline. By introducing the area of interest percentage parameter α,

$$P_{total} = (\frac{\sqrt{A}}{d_{ptp}} + 1)^2 \cdot p_{AoI} \tag{4}$$

Figure 6 gives and overview of the workflow that led us to the total amount of smart light poles.

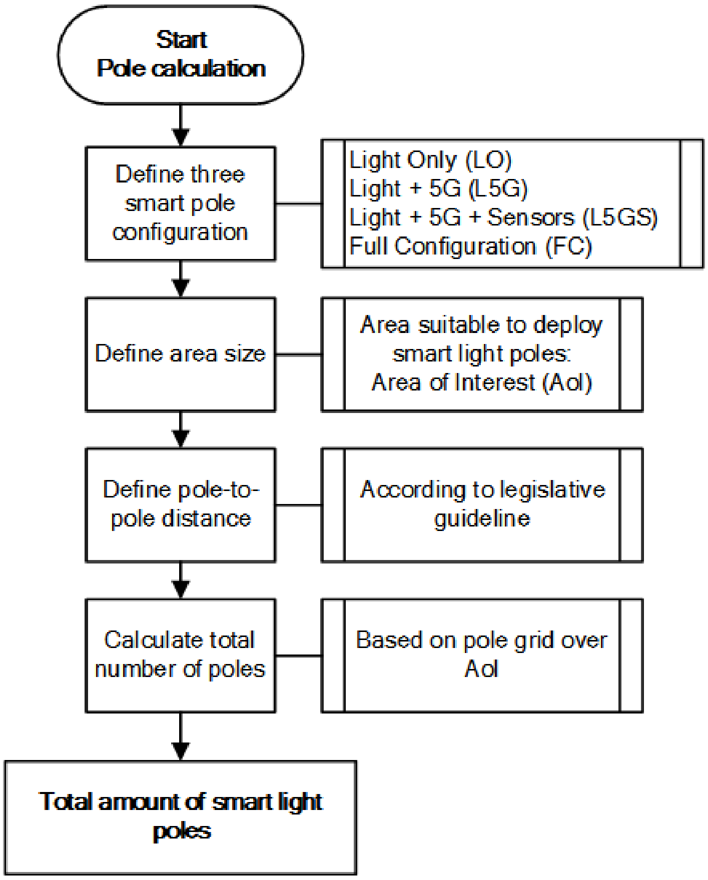

Figure 6: P_{total} calculation overview

Cost data regarding the smart light pole and its components can be found in Appendix A.1.

3.3.2 Number of poles per configuration ($\mathbf{P_{config}}$)

To satisfy different demand requirements, we define zones with different device density and device speed, as shown in Table 3. Based on these zones, we allocate a different mix of pole configurations considering the coverage of pole components e.g. 28 GHz small cells, weather stations, and video cameras.

Table 3: Deployment zones

Zone	**Device density**	**Device speed**	**Example area**
1	Low	High	Commuting
2	Medium	Medium	Suburban
3	High	Low	City center

3.3.3 Average infrastructure cost per pole ($\mathbf{C_{infra}}$)

Given a defined grid-based deployment, we estimate costs for digging the trenches in between poles, installing power and fiber cables, installing protective tubes, casting the concrete base on which the pole shaft will be fixed, reconstructing the street surface, as well as installing a telematics center. The total infrastructure cost is averaged to the number of poles, thus generating an average infrastructure cost per pole. Detailed cost data regarding the infrastructure work can be found in Appendix A.2.

3.4 Cost Evolution Module

In this work, we tried to model the future cost evolution my considering three parameters that occur in product life cycles, namely Mass Production, Volume Sale and Price Erosion. All of the three before mentioned factors were applied in the evolution of the smart light pole costs, whereas we only considered the Volume Sale and Price Erosion parameters for infrastructure/public work related costs. The reason for excluding Mass Production is due the fact that construction companies usually considered that factor in there initial offer for such huge projects. The next sections explain these parameters and shows the values and statistical approach we used in the cost model. The PERT distribution function parameters are presented in the following form:

$$PERT_{CostEvolutionStep}(min; mode; max) \tag{5}$$

3.4.1 Prototype improvement

Since some pole hardware components are under development, we can expect their manufacturing cost to decrease due to engineering optimization, utilization of cheaper sub-components, and reduction in labour caused by mass production. Thousands of these components may be needed to serve an increasing demand for 5G smart light poles by the world's cities. We assumed a 40% decrease in costs for current prototype stage pole components for our static model. To cover the uncertainty of our assumption, we applied a PERT distribution with a mode of 40%, a minimum of 20% and a maximum of 60% for cost decrease due to mass production.

$$PERT_{PrototypeImprovement}(0.2; 0.4; 0.6) \tag{6}$$

3.4.2 Volume sale discounts

Another significant impact on the cost development has the volume sale. We assume that in the near future, there will be potentially many cities interested in becoming a so-called smart, connected city. This will result in a smart light pole sales increase, which has the potential to decrease prices for the smart poles. We furthermore assume that this will lower the costs of production related parameters due to economy of scale effects. The main impact on a higher volume sale is of course associated with the mass production, therefore, we assume a further cost decrease of 10%. We again used a PERT distribution to handle the uncertainty of this estimation by using a mode of 10%, a minimum of 5% and a maximum of 15% for the cost model.

$$PERT_{VolumeSale}(0.05; 0.1; 0.15) \tag{7}$$

3.4.3 Price Erosion

[25] Defines price erosion as followed: Price Erosion is defined as the difference between actual price and potential price of goods and services. The potential price is the price of the item that would have been realized in case of no competition from the competitors. In general, price erosion is a negative price realization in the market. It can be measured on similar products or services in two comparable time periods where there is a continuous decline in price. Price erosion happens with products or services that are similar. In fact, we used a modified definition of the term. In our case, we define it as a long-term cost decrease of especially technical products due to technical improvements in the fabrication processes, the presents of new competitors, the decreasing costs of parts to assemble the pole component, and other influences that have an impact of the costs. For our model, we assume a long-term price erosion of 20% after mass production and volume sale. Once again, we tackle the uncertainty of our assumptions by using a PERT distribution with a mode of 20%, a minimum of 10% and a maximum of 30%.

$$PERT_{PriceErosion}(0.1; 0.2; 0.3) \tag{8}$$

3.5 Today's and Future TDC

To calculate the total costs of the smart light pole deployment **TDC**, we multiply the number of poles in each configuration $\mathbf{P_{config}}$ by the cost of their respective configuration $\mathbf{C_{config}}$ and add the product of the total amount of poles **P**, independent of their configuration and the total infrastructure cost $\mathbf{C_{infra}}$. Equation 9 presents the mathematical formulation.

$$TDC = \sum_{config} (P_{config} \cdot C_{config}) + P \cdot C_{infra} \tag{9}$$

3.5.1 Today's TDC

The model estimates the TDC of today as a function of multiple deployment parameters d_i, as shown by Equation 10.

$$C_{infra} = C_{infra}(d_i) \tag{10}$$

3.5.2 Future TDC

The model estimates the *Future TDC* as a function of deployment parameters and the evolution of key cost items. The evolution of the pole cost includes variations derived from prototype improvement (p), volume sale discounts (v), and price erosion (e). The infrastructure cost only depends on volume sale discounts, price erosion and the beforehand mentioned multiple deployment parameters.

$$\begin{aligned} C_{config} &= C_{config}(p, v, e) \\ C_{infra} &= C_{infra}(v, e, d_i) \end{aligned} \tag{11}$$

4 Smart City Deployment Scenarios

We evaluate the cost model for a minimum deployment scenario and a massive deployment scenario.

The minimum deployment provides uniform and seamless coverage for smart lighting and 5G small cell access. In addition, it provides RTK positioning and low-resolution video surveillance when in close proximity of poles (i.e., basic smart city services).

The massive deployment scenario introduces a more realistic study case in which the area of interest is divided among the three zone types defined in Table 3. Further, it additionally provides high-resolution surveillance, EV charging, video signage via information displays, and drone docking and charging services (i.e. advanced smart city services). We considered a rectangular grid-like pole deployment as a deployment basis with a pole-to-pole distance according to the corresponding city guideline as presented in Figure 7.

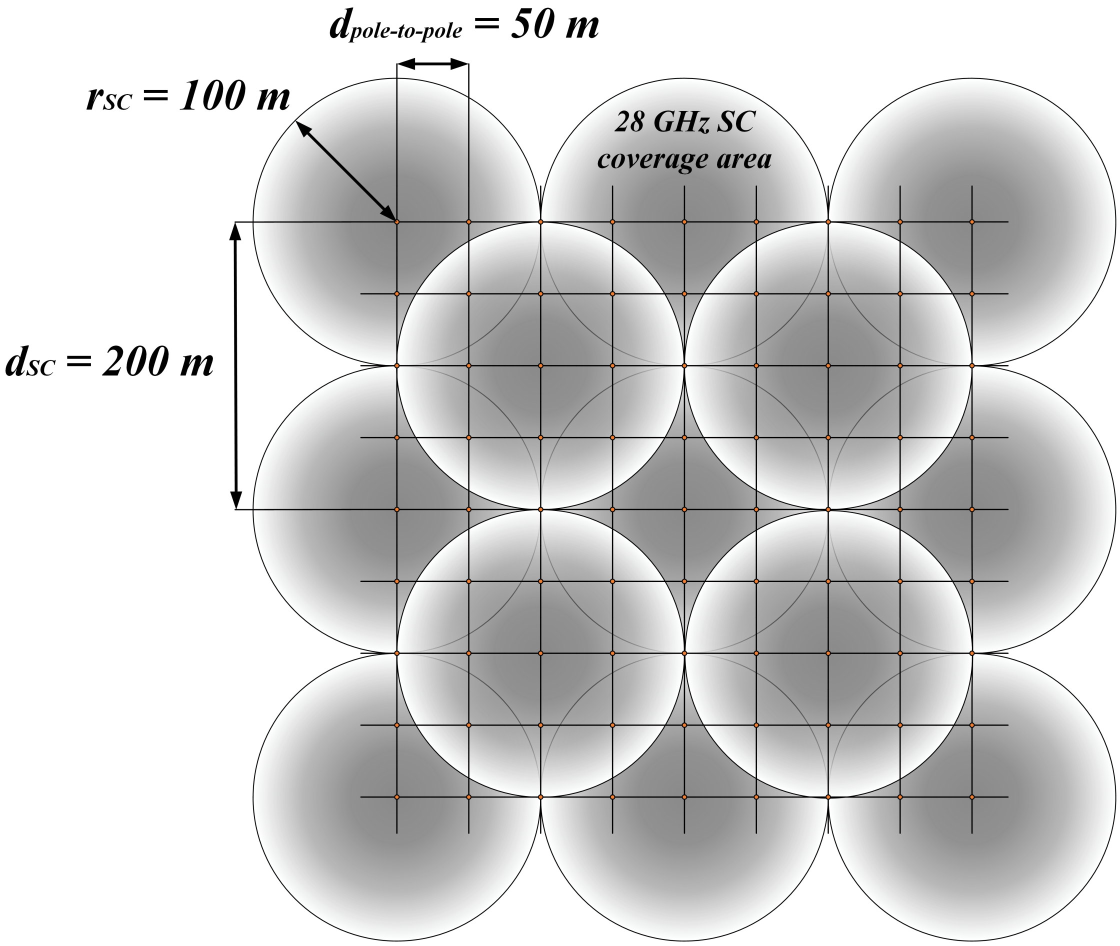

Figure 7: Espoo-specific grid-based deployment structure. Origin of grey circles represents poles with a 5G small cell base station.

4.1 Minimum Service Deployment

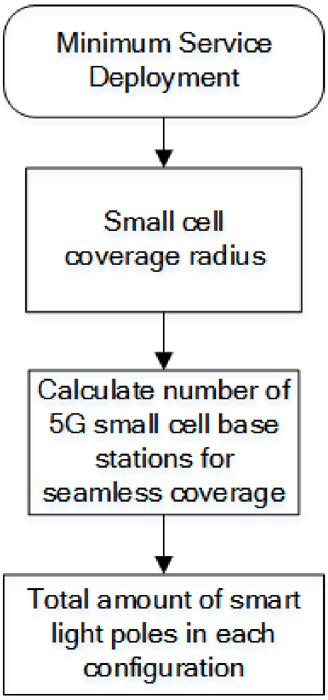

Figure 8: Workflow to calculate the number of poles to be deployed in each configuration

In this deployment scenario, we assume an installation of 5G base stations on poles to achieve a seamless high capacity mobile broadband coverage network in the considered area of interest. That means that we upgrade the deployment model with information about the 5G small cell coverage radius. For the total deployment cost result, we assume a circular coverage radius of 100m for each 28 GHz SC. To consider the different pole configurations, we assumed that half of the poles that need to have a BS, are furthermore equipped with additional sensors and are L5GS configured. The results for our base case are followed:

On total, we need 2890 poles of which 364 have to have a 5G SC BS to ensure seamless coverage, calculated with Equation 12. In order to cover deviations in the actual deployment, we split the 364 poles in L5G and L5GS poles using a PERT distribution with a mode of 50%, a maximum of 60% and a minimum of 40% to consider a need for L5GS smart pole services as well. Furthermore, we vary the SC coverage radius and the ratio between L5G and L5GS poles. Due to different propagation conditions in an urban environment, we varied the SC coverage radius with a PERT distribution function where the mode is 100m, a minimum of 75m and a maximum of 200m.

As shown in Figure 7, we consider a deployment scenario shown in Fig. 2. where each circle origin represents a L5G or L5GS smart pole to assure seamless coverage. Each intersection on the grid is a smart light pole with a pole-to-pole distance of

50 m. By assuming a 100 m circular coverage radius on average for the SC BS, we deploy the L5G or L5GS poles every 200 m on the horizontal line and with a shift of 100 m in every second line.

The model is calculating the necessary number of poles $\mathbf{P_{SC}}$ with the following formula:

$$P_{SC} = (l_{SC} \cdot (2 \cdot l_{SC} + 1)) \cdot p_{CA} \tag{12}$$

where $\mathbf{l_{SC}}$ is the length of the area side divided by the distance between two SCs.

$$l_{SC} = \frac{\sqrt{A}}{2 \cdot r_{SC}} \tag{13}$$

Table 4: Main cost calculation parameters for minimum service deployment

Input parameters	
Area size $\mathbf{A}$:	10 km^2
Pole-to-pole distance $\mathbf{d_{ptp}}$:	50 m
AoI percentage $\mathbf{p_{AoI}}$:	70 %
Total number of poles $\mathbf{P}$:	2890
Small cell coverage radius $\mathbf{r_{SC}}$:	100 m
Nr. of poles with 5G small cell $\mathbf{P_{SC}}$:	362

4.2 Massive Service Deployment

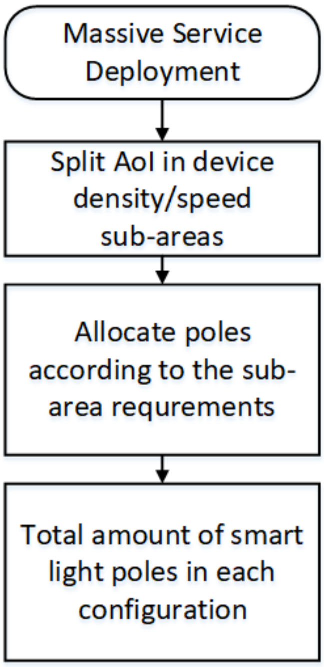

Figure 9: Workflow to calculate the number of poles to be deployed in each configuration

The second scenario follows a very different approach. In the Massive Service Deployment we split the AoI in three device density and device speed sub-areas. We named these sub-areas low/high, medium/medium and high/low where the left side of the slash represents the device density and right side the device speed. A low device density, high device speed area can for example be a street or even a highway where there are on average not as many devices served by one SC in a short period of time, because they are located in a moving vehicle. Whereas high device density, low device speed area could be a main square in a city center with many pedestrians where no cars are allowed to drive. Therefore, the main difference is the necessity of mobile network capacity, surveillance and other sensor services that the smart pole can provide in the right configuration. The size of the sub-areas has to be set as a percentage of the AoI. Furthermore, each of these sub-areas can have a different allocation on LO, L5G and L5GS smart pole configurations. After setting the parameters, the model computes the necessary number of poles in each configuration. To tackle the uncertainty that comes along with the estimations, we perform a Monte Carlo simulation to vary the amount of LO, L5G and L5GS poles using a PERT distribution. The mode is the beforehand calculated number of poles in each configuration and the minimum and maximum is ±20% of the mode value.

This section presents the main results of the cost model. This chapter is divided by the two deployment scenarios. A common conclusion is provided in the final results section in Chapter 6. After introducing the main input parameters and the cost data that feeds the MCS, we present the total deployment costs showing the share of the smart light pole and infrastructure related costs. This is done by showing the mode of the histogram, which is the main result of the simulation.

Table 5: Main cost calculation parameters for minimum service deployment

Input parameters	
Area size $\mathbf{A}$:	10 km^2
Pole-to-pole distance $\mathbf{d_{ptp}}$:	50 m
AoI percentage $\mathbf{p_{AoI}}$:	70 %
Total number of poles $\mathbf{P}$:	2890
Sub-area sizes $\mathbf{A_{sa_i}}$:	3.33 m^2
LO, L5G, L5GS allocation in sub-areas $\mathbf{P_{sa_i}}$:	33.33 %

5 Cost Model Results

5.1 Input Data Summary

This section lists the main input data for the Monte Carlo Simulation. Table 6 shows the pole configuration mix used for the deployments. To calculate these mixes, we assume that 28 GHz small cells have a coverage radius of 100m [13], which defines the fraction of L5G and L5GS poles. We also assume that weather stations have a 500m radius, which is the most demanding in the Full configuration, defining the fraction of Full Configuration poles.

Table 6: Pole configuration mix

	LO	**L5G**	**L5GS**	**FC**
Minimum deployment				
uniform	88 %	6 %	5.4 %	0.6 %
Massive deployment				
zone 1	40 %	30 %	26 %	4 %
zone 2	40 %	40 %	20 %	0 %
zone 3	30 %	40 %	26 %	4 %

Table 7 presents TDC calculation details, including additional input parameters, the number of poles for each configuration, and *Today TDC* and *Future TDC*.

We run a probabilistic sensitivity analysis allowing for variation in certain variables, as shown by the probability distributions in Table 8. As explained in Chapter 2, we selected the Beta-PERT distribution, because it is typically used to identify project risks, given it ability to cover variable skewness. Like the triangular distribution, the Beta-PERT distribution emphasizes the "most likely" value over the minimum and maximum estimates.

Table 7: Deployment details

Input parameters	**Minimum**	**Massive**
Area	10 $\mathbf{km^2}$	
Pole-to-pole distance	50 m	
α	70 %	
Prototype impr. (p)	0.4	
Volume discounts (v)	0.1	
Price erosion (e)	0.2	
Zone alloc.	unif.	33% each zone
Pole configurations		
Total	2890	2890
LO	2526	1060
L5G	182	1060
L5GS	164	694
Full	18	77
TDC results		
Today TDC	48.4 M€	65.7 M€
Future TDC	32.3 M€	40.5 M€
Cost evolution reduction	34.1%	38.4%
Today Min-Mass diff	28.5 %	
Future Min-Mass diff	20.0 %	

Table 8: Variable distributions

Deployment parameters	
α	$\beta PERT(0.6; 0.7; 0.8)$
28 GHz small cell coverage	$\beta PERT(75; 100; 200)$
Weather station coverage	$\beta PERT(200; 500; 800)$
Cost evolution parameters	
Prototype improvement (p)	$\beta PERT(0.2; 0.4; 0.6)$
Volume sale discounts (v)	$\beta PERT(0.05; 0.1; 0.15)$
Price erosion (e)	$\beta PERT(0.1; 0.2; 0.3)$

5.2 Probability Distribution of Today's and Future TDC

By performing the MCS with ten thousand iterations and the before mentioned parameters, the cost model computes the results presented in Figure 10 and 11 showing the TDC with today's costs in blue and with the long term estimated costs in orange. The PDFs give an overview of the possible cost range considering the applied estimations and PERT distributions. We observe how the Future TDC could vary between 28 - 43 M€ for the minimum deployment and between 3 - 5.4 M€ for the massive deployment.

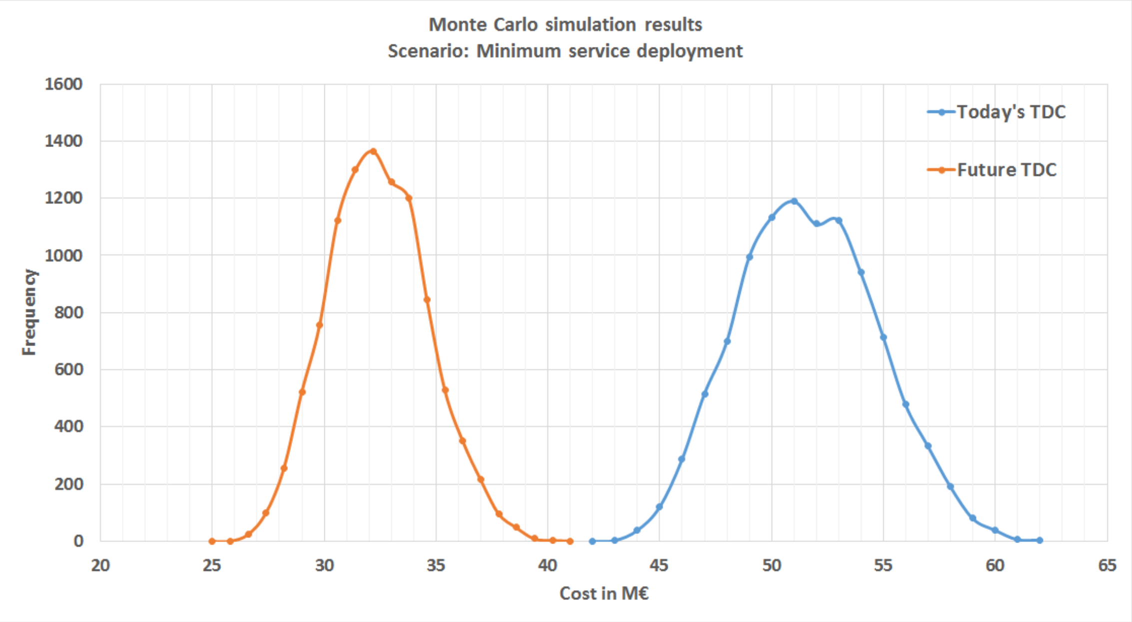

Figure 10: Probability distribution of Today's and Future TDC for the minimum service deployment

Figure 11: Probability distribution of Today's and Future TDC for the massive service deployment

5.3 Effect of Cost Evolution on TDC

Figure 12 shows the mode values of the histogram results for every cost evolution step. It furthermore presents the share of the smart light pole costs and the infrastructure costs. The costs regarding the smart light pole are declining with every cost evolution step.

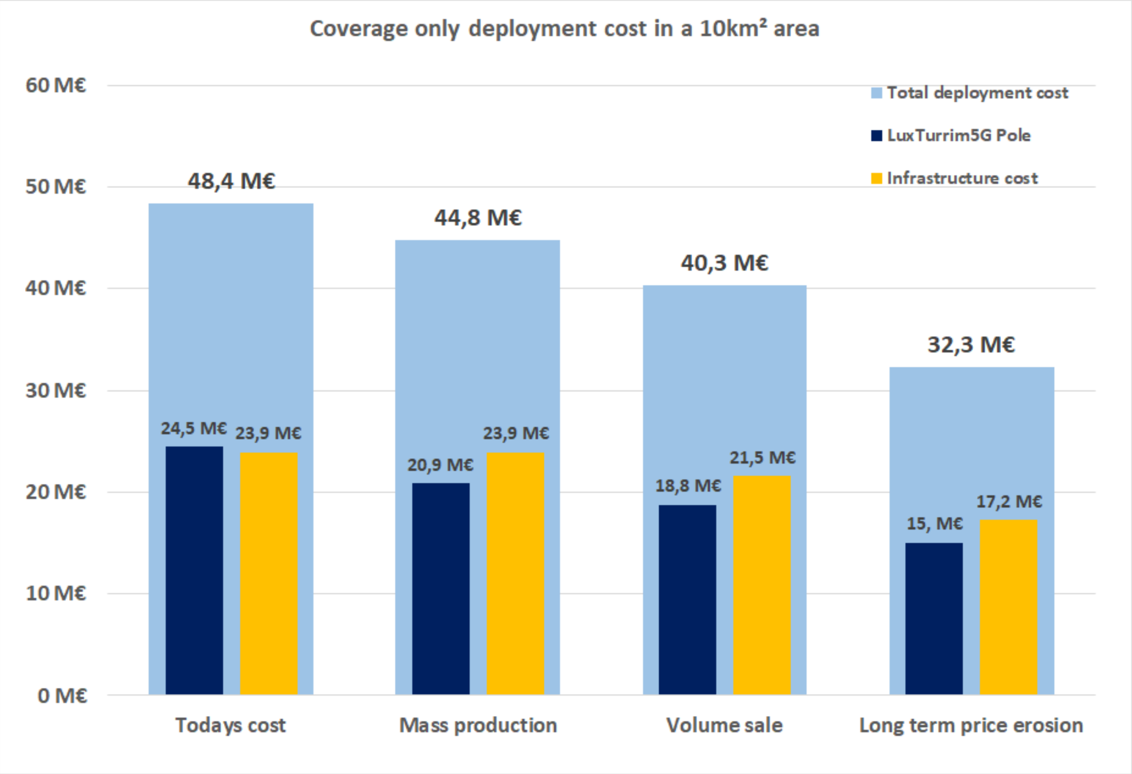

Figure 12: Cost evolution for the minimum service deployment

The mode values from the MCS results for the TDC regarding the massive service scenario are presented in Figure 13. Each of the main bar represents an cost evolution step and includes the share of the smart light pole costs and the infrastructure costs. Again, the costs regarding the smart light pole are declining faster than the infrastructure related costs. Nevertheless, the dominant costs are smart light pole related and is caused by the high number of costly L5G, L5GS and FC poles.

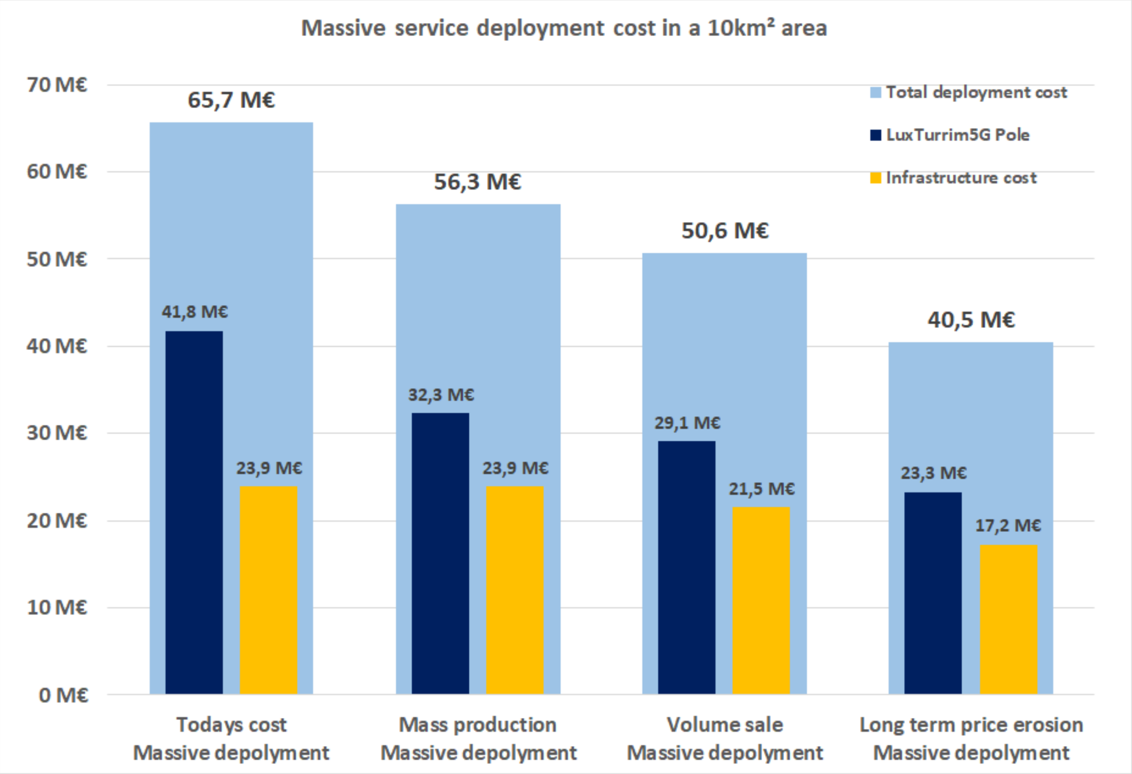

Figure 13: Cost evolution for the massive service deployment

5.4 Relative Contribution of Individual Cost Items

The share of the main cost components on the TDC for the minimum service case are presented in Figure 14. The main bar shows the mode value, the grey error bars indicate the minimum and maximum values calculated in the MCS. Due to the nature of that the considered deployment scenario, it seems reasonable that the pole shaft has the highest impact on the overall costs. Note that the error bars show the change in cost contribution due to probability distributions.

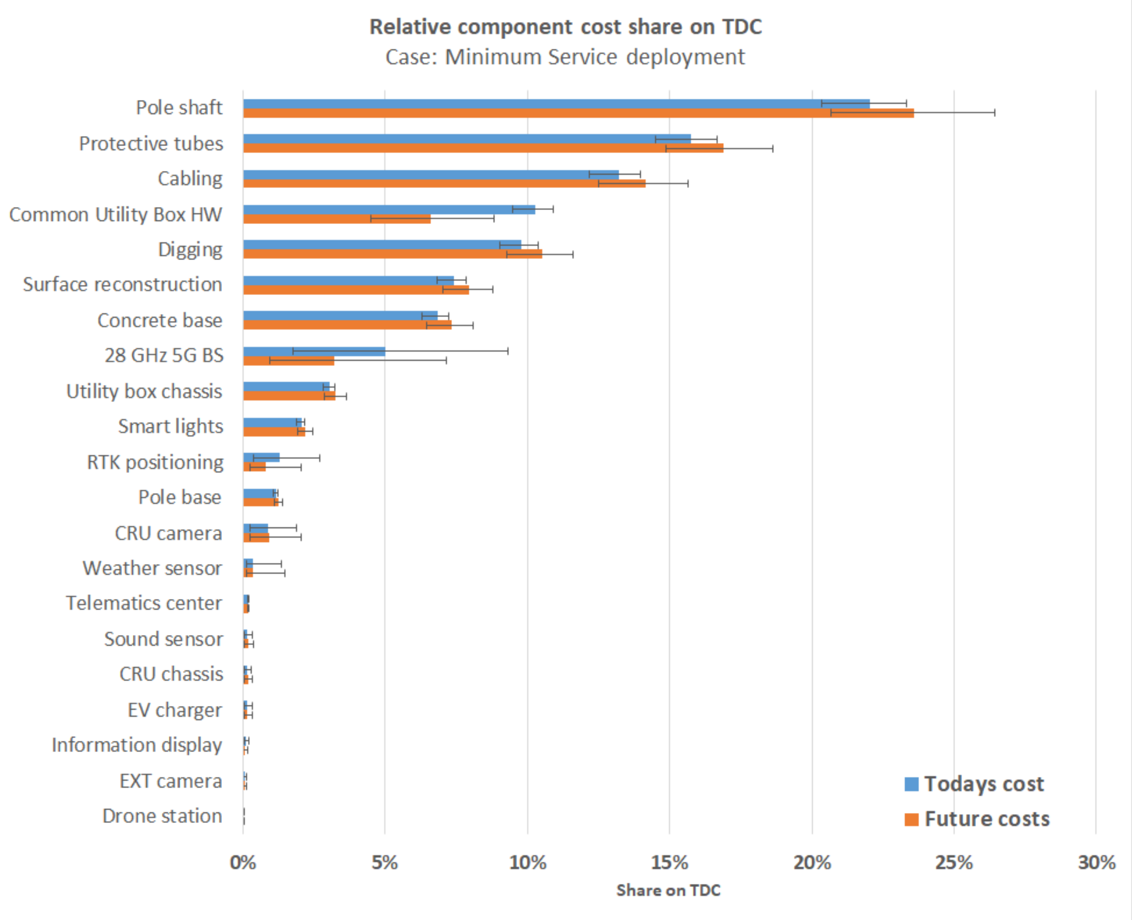

Figure 14: Costs components share on TDC

Figure 15 shows the share of the main cost components on the TDC for the massive service deployment case. Again, the main bar shows the mode value and the grey error bars indicate the minimum and maximum values calculated in the MCS. The main cost component is the 28 GHz 5G small cell base station installed on the L5G, L5GS and FC poles due to the combination of its high cost and its relatively frequent appearance.

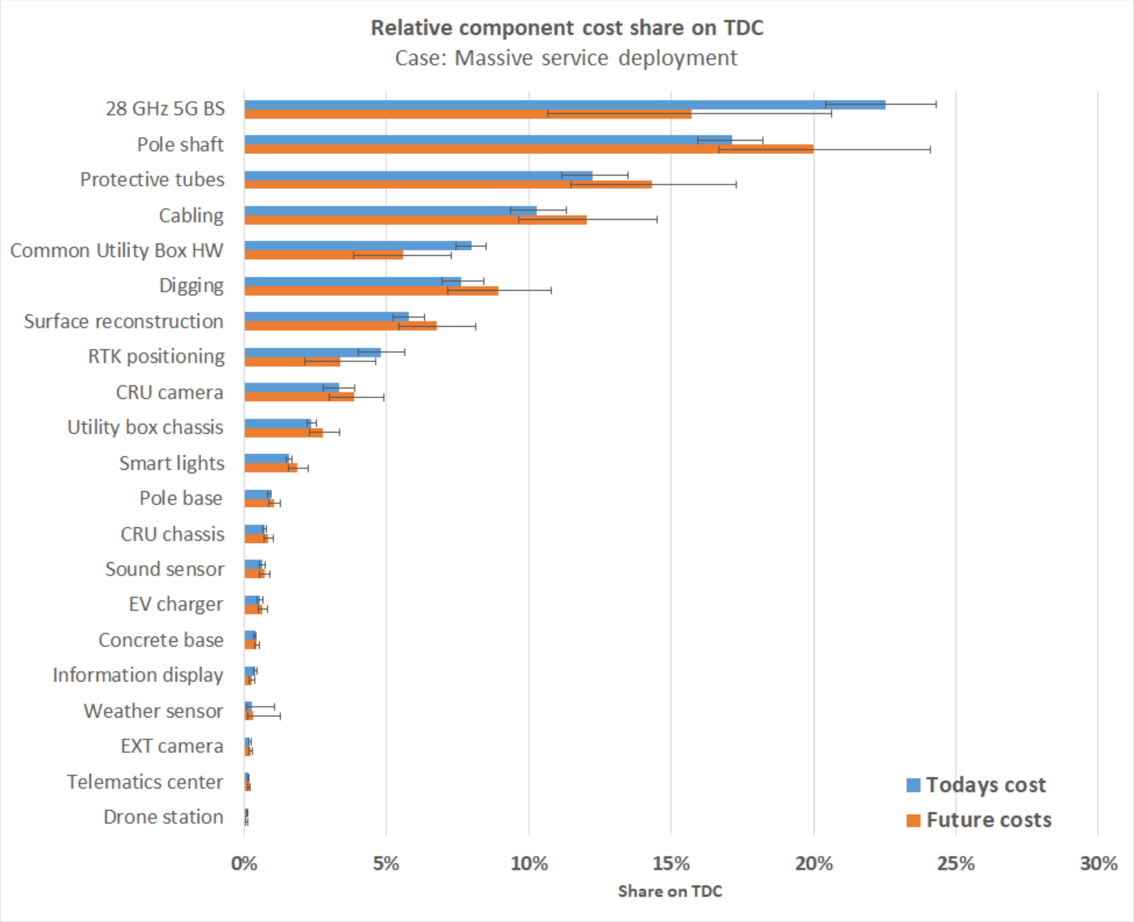

Figure 15: Costs components share on TDC

6 Conclusions

6.1 Results

The key findings of the performed literature review and the cost analysis are the necessity of 5G SC deployment in order to enable the key benefits of 5G mobile broadband and furthermore establishing a smart city. The thesis shows that the smart light pole approach includes high initial costs, nevertheless it is a practicable way to cover all the requirements that comes along with building up a smart city. The cost analysis model presented shows the complexity of such an operation. A multi disciplinary approach forged the cost data input into valuable results.

Depending on the decision about what deployment scenario is going to be carried out, the total deployment costs are varying between 65.7 M€ for the massive service case and 48.4 M€ for the minimum service case, in a 10 km^2 urban area considering today's costs. By applying or cost forecast estimations, this cost will decrease by 30% to 40% of the current costs in the long term due to prototype improvement, volume sale and price erosion.

Even though our results shows a high TDC for smart light pole deployment, one has to consider possible business cases to generate revenues and make the investment profitable. We studied the cost reduction potential caused by the cost evolution of key cost components. When comparing the pole costs versus the infrastructure costs, we observed that the pole costs have a larger cost reduction potential, due to the benefits of prototype improvement. In more detail, looking at the individual pole components, we observe than the small cell base station and the RTK positioning not only have a significant contribution to the TDC but also a significant cost reduction potential. Hence, we recommend cities to promptly start civil works, enabling a fiber-based backhaul for present and future poles, and to select upgrade-able pole designs, which can accept new hardware components as soon as their prices become affordable.

6.2 Assessment of Results

The model assumes a fiber-based backhaul because greenfield deployments facilitate civil works. Thus, poles can be connected to fiber regardless of their current configuration, allowing for future updates.

The main result of the extensive literature review is that a very dense deployment of millimeter wave 5G small cells is mandatory to achieve seamless 5G mobile broadband coverage. This is one of the key enablers for a smart city. By installing those 5G small cells on specifically for that purpose developed smart light poles, it offers the opportunity to install additional connected devices on the pole as well. The high initial deployment costs have the potential pay off by generating revenue by selling the data gathered by the dense sensor network on the smart light poles.

Moreover, it will increase the quality of life for every actor in the established smart city by enabling a smart traffic flow and parking control system, by providing proving more security due to optical and acoustical surveillance, seamless high-speed mobile broadband connections and many more features that a connected city can provide.

Overall, the massive deployment requires an investment that is 28.5% higher (or 20% in the future) while potentially providing advanced services. Hence, it may be worth investing in pole configurations capable of providing advanced smart city services only if these services increase the revenue creation of the network by at least this same fraction. The cost model workflow can basically be applied worldwide due to its modality. Nevertheless, the parameters from other geographical areas and spectrum availability's will vary and therefore lead to different results.

6.3 Future Research

In order to pursue a deeper understanding of the smart light pole deployment economics, it is necessary to go deeper in the OPEX analysis and how to gather revenue from the services provided by a connected city. Future work aims to include brownfield deployments accounting for wireless-based mesh backhaul with mmW antennae. Future work will relate this cost model with revenue models, thus searching for pole configurations and deployment structures than ensure the sustainability of a 5G smart light pole operator. The next steps of the successfully finished LuxTurrim5G project will continue in the LuxTurrim5G+ and the Neutral Host Pilot project. The LuxTurrim5G+ project will focus on enhanced connectivity platforms, smart light pole connectivity, applications and service concepts. The research topics in the Neutral Host Pilot project are data platform and sharing from smart city applications, as well as developing business and operational models for neutral host operators.

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Appendices

A Cost Data

A.1 Pole Cost Data

The cost data are collected from industry experts and from quotations from project partners and field trial. Due to non-disclosure agreements, we are not allowed to show the exact costs for each task. Data is presented in Table 9. Long term estimated cost is estimated via the Cost Evolution Module using parameters defined in Table 7.

Table 9: Pole cost data

Smart light pole components costs		
Component	Today's cost	Long term estimated cost
Weather sensor	8500 €	6100 €
28 GHz BS	8000 €	3500 €
EV charger	4800 €	3500 €
RTK positioning	4100 €	1800 €
Pole shaft	3900 €	2800 €
Information display	3200 €	1400 €
CRU camera	2800 €	2000 €
Utility box	2400 €	1200 €
Drone station	2000 €	900 €
External camera	1800 €	1300 €
Sound sensor	530 €	400 €
Smart lights	360 €	250 €
CRU chassis	260 €	200 €
Pole base	200 €	150 €
SUM	**42800 €**	**25500 €**

A.2 Infrastructure Cost Data

The infrastructure cost data are mainly extracted from construction company offers concerning a 50 000 square meter campus area. Table 10 shows the average infrastructure cost per a single pole regardless of its configuration, provided a 50 meter inter-pole distance.

Electricity and telematics centers, which are mandatory for controlling the power and data flow, are covered under separate concepts. Note that there roughly is one telematics center for every 100 poles. The considered concrete base can be up to three meters in height whereas just 30 to 90 cm is above the ground and the rest is underground. The diameter is usually around 50 cm. Regarding surface reconstruction, it considers the reconstruction of pavement and lawn after the digging and construction work.

Long term estimated cost is estimated via the Cost Evolution Module using parameters defined in Table 7.

Table 10: Infrastructure cost data

Infrastructure work components costs		
Component	Today's cost	Long term estimated cost
Cabling	2300 €	1700 €
Protective tubes	2800 €	2000 €
Digging	1700 €	1250 €
Surface reconstruction	1300 €	950 €
Concrete base	100 €	60 €
Telematics center	35 €	25 €
SUM	**8235 €**	**5985 €**