Systems Engineering Approach to Design and Modelling of Smart Cities

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This dissertation is submitted for the degree of

Doctor of Philosophy

October, 2020

Abstract

Cities shape our social-economic and environmental aspects of life, they are the engines of economic development and attractive places for people seeking employment and better quality of life. However, observed rapid urban population growth challenges cities and sustainable urban development. Among observed major challenges can be named resources scarcity, environmental degradation, security, quality of service, effective resources management and traffic congestion. Despite the effort deployed with conventional urban design, the proposed solutions were unable to significantly respond to existing challenges. Over the past few years, the 'smart city' concept has emerged as a new trend to answer challenging issues related to urban development. The concept of the smart city has been gaining popularity and cities have developed a strong interest in transforming into smart cities. Transformation of a city system into a smart system is meant to improve the quality of life for its people and their way of living, its environment, economy, transport, and governance. Often, observed approaches of transformation tend to present disconnected and fragmented city systems that usually hamper the interaction of city subsystems. Many studies have covered the design and modelling of smart cities, but their focus has been mostly thematic and lacked a systematic and integrative view of a smart city system.

This thesis emphasizes the systematic view of a city system and proposes a novel method of a smart city system integration. It presents a methodology helped by a Model-Based Systems Engineering (MBSE) and Systems Modelling Language (SysML) to develop a model of an integrated smart city system whereby the model was developed and simulated using a system engineering approach. The model brings all subsystems to operate together in one system and focuses on the information perspective of a city system. The core objective is to provide a viable solution to the prevailing integration issue observed in the process of transformation of contemporary city systems into smart city systems. Three scenarios are presented (system's capacity testing, system's information coverage and information delivery in real time) to illustrate how an integrated information platform can be a gateway and easy access to information in a smart city system, as well as a starting point towards modelling an integrated smart city system.

The developed model was further validated, through a case study, this thesis introduces a novel vehicle smart routing system based on the integration approach which maximises the benefits

of completeness of information. The focus is directed to smart mobility and smart environment, two subsystems of a smart city system to deal with pollution in the urban environment. In a smart city environment, travellers are proposed routes which would rather minimize the footprint of their travel on the environment. To achieve this, the proposed system presents an option of a route that has higher capacity to remove air pollution to travellers seeking a route. This practice not only displays an integrated smart city system but also highlights the possibility to travel with less impact on the environment helped by green infrastructure. The results showed that in a smart city environment where ecosystem services are valorised, air pollution emitted by vehicles can be removed by taking into consideration information related to air pollution reduction. The case study presented showed that the proposed technique eliminated air pollutant by up to 1.28%, this is equivalent to 209.19 g $year^{-1}$per trip of CO and 2405.64 g $year^{-1}$per trip of NO_2. These results show that not only an integrated system allows to take informed decisions, but also is beneficial and a necessity. The emphasis of completeness of information through system integration can be a powerful tool to deal with prevailing challenges being faced by contemporary cities.

Acknowledgements

First and foremost, I want to thank the almighty God for blessing me with this research project and for giving me all that was necessary to complete it.

I would like to deeply express my heartiest gratitude to my director of studies Dr Tuleen Boutaleb for accepting to guide me, which she did with excellence. Since day one she has been wonderful! She guided me, inspired me and supported me all along. I never felt alone; I am so grateful and forever indebted to her. To my second supervisor Dr Keith Baker, I had my first cup of coffee with him on Glasgow Caledonian University campus, and he simply and kindly shared his experience and gave me advices that kept me going whenever an obstacle came on my way. Thank you so much! To my third supervisor Professor Slobodan B Mickovski, he was always available whenever I needed him and he is an ocean of awesome ideas. I was honoured to work with a great researcher you are.

I am very deeply grateful to Professor Gerda Siann, for her initiative through Rwanda University Scholarship Scheme (RUSS) that allowed universities in Scotland to offer fee waivers and opened a door for me to pursue a PhD program in Scotland. Many thanks to Glasgow Caledonian University for offering a fee waiver which allowed me to join and be part the department of School of Computing, Engineering and Built Environment. It was an enriching experience and I was honoured to be part the department.

I also want to thank the Government of Rwanda and the University of Rwanda for supporting my PhD by making my stay in Scotland possible.

Furthermore, I would like to thank the research administration staff at Glasgow Caledonian University for their support and Prof. Mario Cools form LEMA / University of Liege for his kindness and priceless support. He opened for me LEMA lab doors and was always there when I needed him. I am, indeed, very thankful to him.

My special thanks goes to my parents, especially my father, for his continuous moral support and his belief in me. Finally yet importantly, I would like to express my special gratitude to my family and friends who helped me by various means and made my PhD a fun and enjoyable journey.

To my loving wife, Mrs Niyubahwe-Naci Victoire, thank you so much to her for being there since day one, standing by my side all along and for her unconditional support and prayers. Her

presence in my life is invaluable and every second of my life I thank God for her being part of my life. May her be blessed now and forever…

To my loving Wife and Son…

Declaration

I declare that this thesis carried out, submitted and presented to Glasgow Caledonian University for the degree of Doctor of Philosophy is my own work. It contains no material previously published or written by another person or material which has been accepted for the award of any other degree or diploma of the university or another institute of higher learning. All other related work of other authors is acknowledged and a list of related references is provided and included in this thesis.

Jules Muvuna

October, 2020

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Peer-reviewed journal articles included in this thesis:

- Chapter 4 is a slightly modified version of:
  - Muvuna, J., Boutaleb, T., Baker, K.J. and Mickovski, S.B., 2019. A methodology to model integrated smart city system from the information perspective. *Smart Cities*, *2*(4), pp.496-511, doi: 10.3390/smartcities2040030.

- Chapter 5 is a slightly modified version of:
  - Muvuna, J., Boutaleb, T., Mickovski, S.B., Baker, K., Mohammad, G.S., Cools, M. and Selmi, W., 2020. Information Integration in a Smart City System—A Case Study on Air Pollution Removal by Green Infrastructure through a Vehicle Smart Routing System. Sustainability, 12(12), pp.1-14.

Refereed conference proceedings

- Chapter 3 is a modified version of:
  - Muvuna, J., Boutaleb, T., Mickovski, S.B. and Baker, K.J., 2016, October. Systems engineering approach to design and modelling of smart cities. In *2016 International Conference for Students on Applied Engineering (ICSAE)* (pp. 437-440). IEEE, doi: https://doi.org/10.1109/icsae.2016.7810231

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CHAPTER 1

1. Introduction

1.1 Overview

Cities shape and influence our social-economic and environmental aspects of life [1]. They are engines of economic development and attractive places for people seeking employment and better living quality. However, cities have seen quality of life degrade over the past decades. Quality of life in cities is linked to a large number of factors such as: commute times, housing availability, environmental health, resource availability, etc. [2]. Among the major challenges faced by contemporary cities around the world include resource scarcity and sustainable urban development. This is associated with traffic congestion, environmental degradation, security, quality of service, effective resources management, among other challenges. Among the major causes of these challenges, the urban population growth [3–5]. While only 32% of the world's population lived in cities in 1950s, more that 50% currently are living in cities, and more will live in cities by 2050 [6]. This increase of urban population has been challenging contemporary cities to find solutions to combine sustainable development and at the same time addressing the rapid growth of urban population. Increases of urban populations create problems that affect the quality of life in urban areas such as inequalities, pollution and feelings of insecurity. It also means that more people need public services, result in more cars on urban road networks, more parking spaces are required, more people need health services, more educational institutions are on demand, etc. Associated demographic issues include population aging and migration, among others [7], and put pressure on demand for resources, infrastructure , and induce accelerated urbanisation to cope with the high demand generated by the growth of urban population. All this come as challenges to sustainable urban development and make the existing complexity of city management even more complex. To ensure sustainable development of cities with such a boom in urbanisation and associated challenges, cities around the world have adopted the smart city concept and the continuous growth of the global urban population has been its driving force.

The smart city concept is considered as a good solution to the current cities' challenges [8]. It offers opportunities to overcome challenges faced by contemporary cities and uplift the citizens living standards [7,9]. It is believed that the smart city concept is the most efficient and cost effective way of delivering services faster and efficiently, and can improve the quality of environment and daily activities of people living in urban environment [8]. To better understand the smart city concept, much work has been done trying to define it. The findings from analysis of the literature shows that the concept itself is complex, given the large number of definitions that can be found [1,8,10]. It was shown in [11] that a shared definition of the concept is not available. It was claimed that there is no universally accepted definition of the smart city concept, which make conceptualisations of a smart city vary depending on the level of development and the context of a city, among other factors [9]. It was further said that trying to find a one clear definition of a smart city concept would lead to many alternatives with ambiguous meaning [12].

Cities are complex systems with different subsystems or domains [7,9,12] and smart cities are no exception. This is no surprise that defining a smart city concept is not a straight forward task and its conceptualisation displays the same complexity [10]. Despite the observed complexity and lack of conceptualisation of the smart city concept [10,12], its popularity has not stopped to grow. This concept comes with more analogous terms, such as virtual city, intelligent city, ubiquitous city, knowledge city, etc. – and all were blamed to be techno-centric and to lack “people” component [13]. However, it is believed that the smart city concept is the most efficient way to deliver to cities fast and efficient services [8] and also to improve the environment and daily living. Smart city concept and its ability to allow sustainable development and improve quality of life has been gaining popularity and have spread all over the world.

The smart city relies on use of technologies on a large scale to support better offering public services and dealing with other challenges they are facing. The benefits expected from smart cities are to efficiently address sustainable development related issues, to address public services delivery challenges and contribute to improve urban quality of life. The literature shows that this concept is still yet to be well understood and defined [1,8], and the lack of proper conceptualisation allows many cities to proclaim themselves smart, and make the notion of smart city to be sometimes used without consistency [10]. A number of cities around the world defined themselves as smart cities but without clear definition and conceptualisation, and without knowing what it takes for a city to be considered smart, it is difficult to confirm if they are really smart.

A city system is identified with various subsystems or dimensions [5,13]. While a smart city was presented as system of six subsystem for the first time by [14], many work endorsed this representation of a smart city concept [1,7,15,16]. There have been a number of conceptual approaches to smart city that led to a variety of interpretations with different conceptualisations of the notion. Some focused on understanding the role of stakeholders with regards to smart city through a triple helix conceptual model and a modified version of it [17–20]. They studied the knowledge based urban economy [17] and proposed the potential of technology in a smart city [18]. Others presented a model resulting from combination of institutional, human factors, and technology and the application of the model to formulate strategic guidelines for a successful smart city [21]. More was done by [20] who maintained a need of a theoretical approach for the concept build considering goals rather than means with which the goals can be achieved. The most popular of the developed models to understand the smart city was presented by [15] and presented six subsystems/components: mobility, environment, governance, people, living and economy. The work presented a smart system with six dimensions, or a system with six subsystems and, through an integrative and comprehensive approach, proposed a classification of smart city projects and their integration. More research focused on interconnectivity and integration [22–24] and highlighted what a fully smart city is [16] through an analysis of city transformation. While [16] presented 3 levels of smart cities: low, medium and fully, a city to be called a smart city must be very advanced, not only in one or two subsystems but all six subsystems. This is presented by [25], who discussed that it should be well established, integrated and operational. Information and Communication Technology (ICT) is observed as the main enabler of smart cities; and cities' governments, technology vendors, and researchers have shown high interest in smart cities concepts and have been trying to explain and defining it.

In brief, a city is a complex entity which is comprised of a variety of subsystems which are all connected and complementary and all combined make a city system. Over the last few decades, cities all over the world have been active into the process of transformation to solve the faced serious challenges related to urban sustainability. Progress in technology in recent decades has unveiled a number of new opportunities to facilitate and enable smart city realisation. The currently known representation of smart city is a system of six subsystems. Therefore, a city system is a set of six subsystems working together as whole like interconnected network.

To transform a city into a smart city means transformation of all subsystems into smart subsystems and bring them all together on one single platform to function as one entity. In [26], the authors identified two transformation approach from city to smart city. However, among the major issues faced by many cities through transformation process include how to successfully integrate all the subsystem and bring them together on an integrated platform that gathers information from all the subsystems for a more accessible and reliable information and services to the public. A city, as a complex system [9,27], its transformation can be complex as well [28]. To cope with the complexity, the process of transformation of a city into a smart city has shown disconnection and lack of integrative and systematic view in the literature [13,23,29]. Although such practice might have brought solutions, it was argued that it will make the city system even more complex, and that cities to be smart should first achieve integration and efficiency [30]. It means that to redesign a city system into a smart city system means to transform it as whole and to make sure that all subsystems remain interconnected and integrated.

While it was argued that a city cannot become smart just via technology, transformation of a city into smart city relies heavily on information technology and seamless communication between all smart city components. A work by [15] studied various aspects relating smart cities with emerging technology. Their findings showed the necessity of integrating the smart city concept with information technology for effective operation of smart cities.

1.2 Motivation

To cope with challenges, cities around the world are aiming to become smart. Some have already started proclaiming themselves smart. However, it was observed that the approaches through which cities are transiting to smart city lacked systematic view and linkage in architecture, was fragmented and disconnected [13,23,29]. A city is a system of systems and is at the same time complex [7,9,12]. To cope with this complexity, the transformation of a city into smart city was observed to be thematic which displayed a fragmented system of a smart city. This meant that, considering the information perspective, information will end up stored in many and various disconnected systems, making it difficult to share information seamlessly. It will be difficult to make connection of all elements of a smart city system and management of relationship between individual systems. It was argued that a city cannot become smart by infusing technology in subsystems, one by one separately, but rather by considering it as one entity, transforming it as whole and keeping it integrated and connected [13]. The principal motivation of this research was to develop a methodology in which a model of an integrated smart city system highlight how an integrated smart city system could be achieved. The developed model focused on the information perspective and considered the city system as a whole. An initial testing of the model was presented through a case study.

1.3 Aim and objectives

The aim of this research is to develop an integrated model of a smart city using novel methods that valorises a systematic view while transforming a city system into a smart city system.

The key objectives of this research are:

1. To critically examine existing definitions of a smart city concept, as a viable solution to challenges faced by contemporary cities, and draw its definition in the context of this research.
2. To develop a new methodology of modelling based on Model-Based System Engineering (MBSE), a methodology which is normally used in software engineered systems development, and SysML, a systems modelling language, to design and test an integrated smart city system model without losing site on the systematic view of a city or fragmenting the city system. Perform an initial testing of the developed integrated system model.
3. To validate the model through a case study focusing information exchange across the model and through a smart vehicle routing system. The process choses two subsystems with the aim of highlighting the need and benefit of having the integrated model.
4. To explore the implications of the developed and validated model of an integrated smart city system.

1.4 Scope

The literature presents many definitions of a smart city system which displays numerous perspectives, and among them, the information perspective. While the approach presented in this work allow the possibility to regard the smart city system on all possible perspective, this research focused on the information perspective to develop and highlight an integrated model of a smart city system. It emphasised the systematic view of a city and approaches of city transformation into a smart city to address the observed thematic view throughout the process of transformation of a city system. To achieve the objectives, a review of literature on smart city was done to deepen the understanding of the concept of smart city and attempt defining it in the context of this work, after which a methodology based on Model-Based Systems Engineering (MBSE) approach System Engineering Modelling Language (SysML), was developed and used to model an integrated smart city system. The model emphasised the integration of the city system to bring subsystems of a smart city system to work together on an integrated platform focusing on the information perspective. The initial validation of the model was presented through illustration of three scenarios that tested the capacity of the system, its ability to target people concerned with particular information and the delivery of relevant information in real time. Further validation of the integrated model was done through a case study in which, emphasising on integration of a smart city system, and focusing on the information perspective, an integrated model of a smart city system took advantage of integrated information to remove air pollution using green infrastructure through a vehicle smart routing system.

This research applied model based system engineering methodology and system engineering modelling language to design and test the model. Integration with other tools for co-simulation were out of the scope of this research.

Six subsystems of a smart city system were identified to be integrative part of a smart city system. To highlight the benefits of an integrative view, the developed model testing focused on information exchange across two of the six subsystems of the smart city system.

1.5 Main contribution

Aligning with the aim and objectives, the main contribution of this research are the following:

- Cities are considered key elements of the future and transformation is now taking place from cities to smart cities to counter-react on challenges faced by contemporary cities. The smart city concept has become popular in the international policies, but still, the literature has no one-size-fits-all definition. This means that, so far, the smart city concept is defined depending on consideration of particular perspectives. Chapter Two of this thesis analyses the existing definitions to deepen understanding of the concept and shade more light by defining the concept in the context of this research.

- In line with the objective of understanding better the city system and the process of transformation of cities into smart cities, Chapter Two of this research analyses the existing transformation approaches of the system and exposes the advantages and disadvantages of the existing approaches of transformation with which a research gap was identified.
- A new transformation approach of a city system into a smart city system is another contribution of this research. A new methodology which applied a model based system engineering approach was developed. By using the system engineering modelling language described in detail in Chapter Three, an integrated model was developed and tested under particular scenarios in Chapter Four. The major contribution of this new approach is that it looked at the smart city concept with a systematic view and sought to integrate the smart city system by developing a methodology of the city system transformation into a smart city system where all the six subsystems of a smart city system worked together and seamlessly interacting as an integrated system.
- The methodology and the integrated model presented with initial validation in Chapter Four is further validated in Chapter Five through a case study in which information exchange across the model through a smart vehicle routing system emphasised the necessity of an integrated system of a smart city by exposing its benefits.

1.6 Thesis outline

This thesis is structured into 6 chapters, and their content is summarised as follows:

Chapter 1 introduces the current status quo of contemporary cities and major challenges they are faced with. It presents the motivation behind shifting from contemporary cities to smart cities, and states the aim and objectives of this research. This chapter also presents the main contributions which lay the foundation of topics to be discussed in details in later chapters.

Chapter 2 presents an overview of the advances in research with regards with the smart city concept. It explores the challenges faced by contemporary cities as motivating factors of the smart city concept. It explores the definitions of the concept, its potential, and the main subsystems of a smart city system. Later, it identifies the knowledge gap.

Chapter 3 conceptualises the smart city system. To allow a systematic view of the city system, this chapter proposes a discussion on the MBSE approach and SysML as potential approach to model and design an integrated smart city system to be developed in chapter 4 and attempt the initial conceptualisation of the concept.

Chapter 4 presents a model developed using a methodology based on MBSE and SysML. It is an integrated model which focuses on the information perspective of a smart city system. It illustrates the structural and behavioural of the system and three scenarios are presented to illustrate how an integrated information platform can be a gateway and easy access to information in a smart city system.

Chapter 5 presents a novel vehicle smart routing system which is used to validate the model. This is done through a cased study, a viable solution to the prevailing integration issued while transforming contemporary cities into smart cities.

Chapter 6 gives a summary of the main conclusions of this research and proposes and gives suggestions for potential future work.

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CHAPTER 2

The smart city concept – A review of literature

The chapter identifies what challenges being faced by contemporary cities that are going to be solved by the smart city concept and how by exposing the potential of the concept. It also discusses issues related analogous terms to the 'smart city' term, explores how a smart city is defined, identifies the main subsystems of a smart city system and identifies what makes a smart city system. This chapter aims to understand the advancement in the smart city area and identifies existing gaps. With this chapter, a definition of a smart city was drawn in the context of this research.

2.1 A perspective on contemporary cities

Cities are places with high yield economically and more of social and cultural benefits [23]. They are extremely complex [16]. Cities play an important role in aspects such as social and economic and have a big impact on the environment. It was argued that cities are hubs of human activity, a place where demands in terms of economy, society and environment are magnified and where urbanisation causes many important and significant transformations on economy, social and demography [31]. Urban areas includes industrial areas, commercial areas, administrative areas, residential areas, etc. [8]. Over decades, cities have been facing a rapid growth of it population which imposes stresses on urban quality of life and on the environmental. Urban population trends showed predictions that by 2050, urbanisation will be 66% while it was 54% in 2014 and 30% in 1950 [31]. Another work by [32] showed predictions where up to 70% of the earth's population are going to live in urban areas. Many more other researchers showed consistency with these predictions [8,24,32,33]. The increase of urban population induces extra demand on services and resources, and while there might be a wish of more green spaces and less vehicles on the road networks, the ever-growing urban population seems like an major obstacle [16]. For sure cities are attractive places and people move there because they hold most of economic opportunities to offer in a variety of aspects, they move there seeking benefits they cannot obtain from the contemporary rural life.

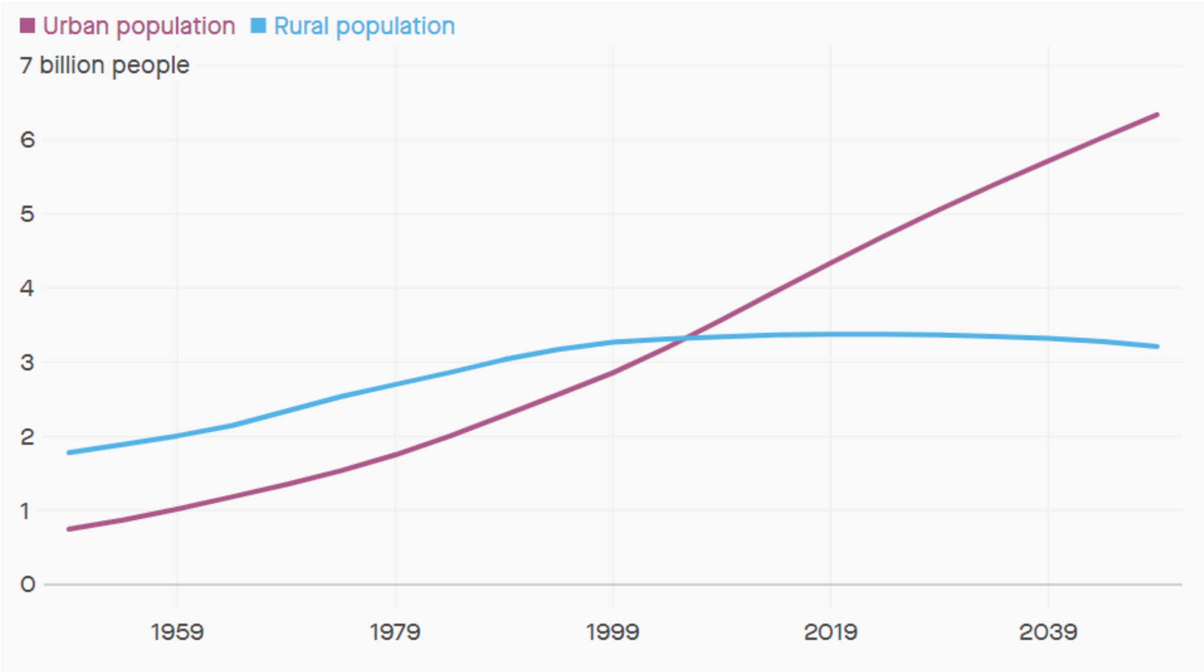

Figure 2. 1 World population growth: urban vs rural population [34]

Figure 2.1 shows the distribution trends of population in urban and rural areas. It is true that urbanisation has greatly improved the standard of living with easy access to water, education, sewage systems, etc., but the rapid increased of urban population not only imposes pressure on already scarce resources but also influences various aspect of the quality of life [33,33] and accelerate urbanisation. Therefore, the observed increase of urban population generates challenges which hinders sustainable and socio-economic development.

2.1.1 Challenges of contemporary cities

Given estimation that more people will live in cities, up to 70% by 2050, cities are expected to be bigger (see Figure 2.2), very densely populated, and more resources are going to be required to accommodate their populations. Most of cities are hubs of universities, hospital, businesses, commerce and many more other institutions that gather and attract a large number of people. With the observed urbanisation speed-up, particularly in developing countries in Asia and Africa [8], cities are faced by challenges which are mostly generated by increased population. More people threatens the environment and rapid urbanisation put strain on existing infrastructure. Among the major challenges faced by cities include environmental degradation, scarce resources such as water and energy, good governances to maintain an acceptable level of service, etc. Thus, rapid urbanisation induced by rapid urban population growth creates new issues and challenges [8].

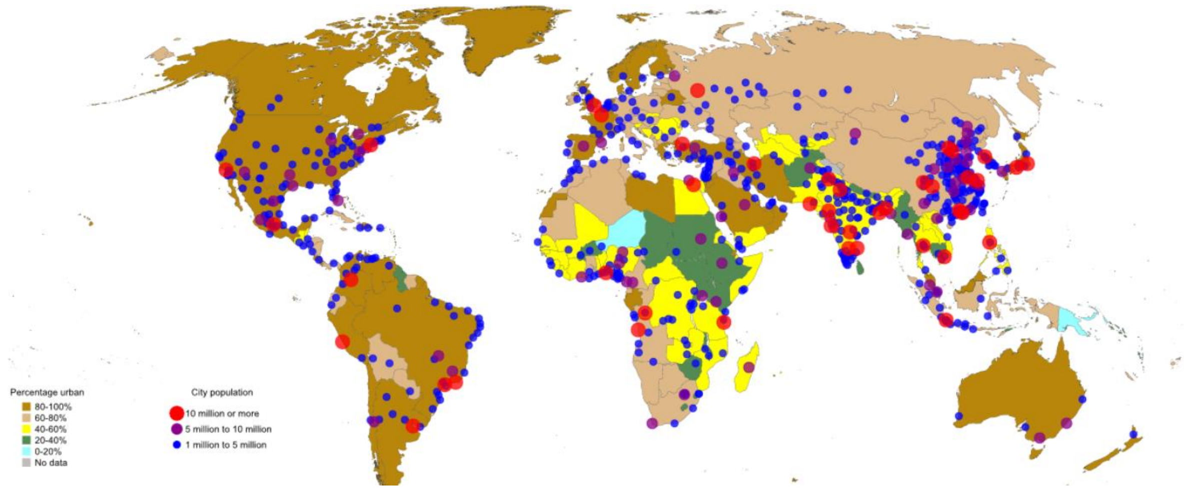

Figure 2. 2 Percentage urban and urban agglomeration by size class, 2030 [35]

Many studies agree that most of the new challenges facing cities are results of the urban population growth and among them: [36] identified maximum use of natural resources which causes environmental and ecological problems. [37] Identified increased public disorder due to overcrowding, degradation of environment, air pollution, increase crimes, access to clean water, neighbourhoods security and efficiency of infrastructure. [8] Argued that the speed of urbanisation is considerable fast and the consequences associated are mostly related to infrastructure problems. [33] Identified housing challenges related to utilities (water and energy), health care, education and employment. [38] Rather focused on social related challenges such as urban congestion, environmental related challenges such as increased urban pollution and economic related challenges such as rising interspatial inequality. [39] Identified challenges related to economic prosperity and social wellbeing and challenges associated to flows of resources and waste management. [10] Focused on challenges related sustainable development and distribution of goods and services. [40,41] Identified challenges related to infrastructures and focused on water infrastructures, their maintenances, increasing demand and contaminants due to rising population level. Challenges identified by [23] included reduced quality of life in urban settlement due pollution, inequality, security and ageing population.

[42] Identified challenges related to service delivery and transportation. [43] Identified challenges related to pollution, security, traffic congestion, maintenance of infrastructure, asset management, among others. [44] Focused on increased energy consumption. [45] Focused on infrastructure and associated loss of functionalities and among the challenges mentioned, human health concerns, traffic congestion, waste management, deterioration of infrastructure, and scarcity of resources.

The list of challenges being faced by contemporary cities due rapid growth of urban population and associated rapid urbanisation are many. What is clear is that we are in an urban era where a large number of the world's population lives in cities, and even more people are projected to move from rural to urban areas. It will speed up urbanisation, and to cope with this growth and flux of people, management of these challenge was found to be a necessity and a must. Innovative solutions need to be found to address the challenges and maintain a good quality of life.

2.1.2 Solutions to cities' challenges

As mentioned earlier, while urbanisation process improved peoples' standards of living [8], rapid increase of urban population together with rapid urbanisation challenge cities and hinder sustainable development [33]. Cities are main hubs of, not only economic but also cultural and social development. It is no doubt that cities are different in one way or another, but the challenges they face are generally similar, from transportation challenges to resources scarcity, waste management, housing shortage, etc. Most of the places around which our everyday lives evolve are located in cites. However, cities are now facing many and complex challenges. These challenges need to be identified, appropriate solutions need to be identified as well and implemented to keep cities liveable. We are in an era where globalisation has advanced and competition among cities to attract tourists and investors has never been so pronounced. Mayors of cities are taking leadership to find solutions with creative and innovative forces to attracting talents and speed-up sustainable urban development. More often, the major objectives are to improve quality of life of citizens in present and future and to operate transformation towards sustainable and inclusive development. While making effort to find solutions, new names started to appear. For example: a creative city [46] where the authors describe methods and strategies of urban planning that allow to examine a way in which citizens can think and act creatively to unleash skills of young and elderly, thus, harness the imagination of people. Digital city is another solution in which information is collected to allow creation of a public space for people living in cities [47]. It was shown that each digital city had its own goals depending on how it organised itself and project put in place. Among other names that come as solutions to contemporary city challenges include intelligent cities, information cities, innovation cities, knowledge cities, sensing cities, ubiquitous cities, virtual cities, wired cities, green cities and the most popular being smart cities. Smart cites has been gaining popularity over decades, and like all the other naming, the smart cities concept rose from issues and challenges caused by rapid urbanisation [28]. It is believed that by investing in modern smart cities, challenges of cities will find their solutions. Many countries have launched projects of their own in line with the smart city concept to resolve issues and challenges arising from urbanisation [8].

2.2 The smart city concept

Despite the gained popularity of the smart city concept, it is still not fully understood. The concept itself appears not to be neither the simplest nor the easiest to define. This section is going to explore existing definitions of the concept, attempt to define it and highlight its evolution and potential.

2.2.1 Understanding the terms analogous with 'smart city'

Observation in the literature shows that the term 'smart city' comes with other analogous terms which can create confusion and ambiguity while attempting to understand the smart city concept. What all these terms have in common is that they all refer to the use of information and communication technology (ICT). It was observed that most of the terms could be used interchangeably to 'smart city' which created a feeling that questioned the existence of the term. A good example is [15] in which it was argued that terms like intelligent city, wired city, sensing city, information city and ubiquitous city are alternative terms to smart city. However this was found not consistent with [8] in which they described the terms and showed how these terms were different to smart city. Other identified terms included: a wired city [48]; an innovation city [45]; a virtual city where a city is a hybrid concept consisting of a reality with real inhabitants and physical entities parallel to a virtual counterparts, cyberspaces, and visualise urban elements within the virtual space [1]; a sensing city [49]; an information city

[50–52]; a knowledge city which was described as a city that encourages nurturing and is enabled by cloud technologies [53,54]; a ubiquitous city which was described as an extension of a digital city characterised by making ubiquitous computing available everywhere in urban elements [55] and which is a product of inclusion of sensors and computer chips in urban element. This showed lack of understanding and complexity of the terms smart city.

Before defining the smart city term, we need to first understand better analogous terms and identify how they differs or are related. Terms like information city, wired city, invisible city, telicity, intelligent city, virtual city, cyber ville, etc. are among few of the long list that can be found in the literature to identify a city of the future [56]. The two of the most popular term observed in the literature are:

Digital city

Literally, the term digital makes reference to binary digits '0' and '1'. The term has been used since 1990s relating to city to refer city transformation enabled by digital technologies [56]. The term was well explained in [56] where the authors showed how it started to be discussed. They showed that the term was originally linked to ICT in public administration and e-government where they sought transformation of cities in virtual cities, created a dimension that allowed a relationship between people and services virtually. Making reference to [57], a digital city involved networking, information technology and visualisation to make access to resources, environment, economy and social data. Among other descriptions, a digital city was a city that combined computing infrastructure and communication to meet the governments' needs [58] and a city whose procedures, information and communication were all digitized [8]. Albino in [1] identified the final goal of a digital city to create an environment to allow collaboration, information sharing, seamless experiences and interoperability. Mainly, it was confirmed that a digital city is not necessary a smart city, but a smart city can be a digital city [8].

Intelligent city

Intelligent cities transform life and work using information technology [1]. It was argued that intelligent city is very often considered as synonym of smart city even though it shouldn't, and that the difference between intelligence and smart was more often misunderstood [8]. It was said in [39] that smart city could be substituted by intelligent city and the authors described it as a system which is used intelligently to have people's behaviour modified to sustainably use available urban infrastructure. In [15,45] not only it was said that intelligent city can be referred to as smart city but also as digital city, information city, knowledge-based city, wired city and ubiquitous city. The work by [45] displayed disagreement with [8]. In [8] it was argued that a smart city is an intelligent city under some particular conditions. A more clear description of intelligence by [8] showed that a smartness, which has self-adaptive capability, was different from intelligence described as having a quick mind and being responsive to feedback.

In summary, what was observed is that all these terms connect the city to technology. Many terms are used interchangeably to the term smart city, this should not be the case. While a smart city can be digital or intelligent, a digital city and an intelligent city aren't smart city. Smart city included people components among others [1], and therefore, more than technology is needed to make a city smart. Hence, a smart city is not exactly same as digital city or intelligent city. In a digital city, information, communication and procedures have been digitize; an intelligent city is a digital city which has layers of intelligences that allow to make decisions enabled by artificial intelligence; and a smart city is an intelligent city which is focused on practical and user experience application. A smart city is a more advanced version of intelligent city. It is more inclusive with more dimensions other than technology, more notably the human dimension. All the other terms were found to be more specific and less inclusive while the term smart city was more inclusive than the others.

2.2.2 A definition of the smart city

Even though it is not yet very fully understood, the smart city concept in now popular and its importance has been increasing in the agenda of policy makers [11]. For some reasons, which can rather be related to the complexity of the city system, the smart city concept still has no universally accepted definition. It was argued that perhaps the reason of the absence of a general agreement on the term smart city is the fact that it is applied to both hard domains (energy grid, water management, mobility, etc.) and the role they have on the systems when information and communication technology (ICT) is applied on them and soft domains (culture, education, social inclusion, government, etc.) on which ICT is not decisive when applied on them [11]. It was said that it could be both simple and difficult to have a formalised definition depending on a perspective which could be a function or process to restructure procedures of a governing body of a city [59]. The common description of a smart city shows that it is one that uses ICT to make all aspect of a city (e.g. administration, transportation, resources management, etc.) more intelligent and efficient [8,15] and an urban area that provide high quality of life for its residents [1,24,60]. The authors in [8] observed that it was difficult to have a formalised definition of the concept and proceeded to a classification task while attempting to define the smart city concept. Another observed definition which showed similarities to many others was found in [61] which focused on the operation aspect and the definition showed that being smart for a city is being run sustainably, efficiently and intelligently. Another observation in [15] on how the concept was being defined revealed that majority of smart cities' definitions mainly focused on the role technology. This is not surprising given that technology is one of the main enabler of smart cities. In [62], Yang defined a smart city as a city in which everything is connected. In his definition of a smart city, he described it as a city in which everything is connected by using data collected and gathered by sensors and video cameras.

This work analysed some more definitions found in the literature after which attempted to define the smart city concept in the context of this research. Our observation showed that we could group the observed definition in three groups. The first grouping of definition focused on the technology perspective of a smart city (see Table 2.1), the second group showed a focus on human perspective by putting forward people residing in cities (see Table 2.2) and the third group showed a focus on not only one perspective but more than one perspective of a smart city to elect a definition (see Table 2.3).

Table 2. 1 Definitions of a smart city with a technology perspective

Definition of mart city/smart cities	Reference
ICT infused city infrastructure to enable or allow in-depth monitoring and maintenance of different features and services in the city.	[63]
Uses all available resources and technologies intelligently to create an integrated and sustainable urban environment which is more liveable.	[64]
A city in which everything is connected by using data collected and gathered by sensors and video cameras.	[62]

A place which uses sensors, electronics, and advanced and integrated materials such networks of computerised systems (databases, tracking and decision-making algorithms).	[65]
A modern territory which is enabled by advanced technology to allow intellectual ability that enables to deal with various technical, social and economic challenges. It also uses computing technique to enable infrastructures to deliver superior services.	[66]
Takes advantage of sensors capabilities and communication integrated into cities' infrastructures to optimize daily operations of life and at the same time improve every one's quality of life.	[67]
An urban environment conceived to be supported by information and communication technologies (ICTs) to be able to offer advanced and innovative services to citizens and improve overall quality of life.	[68]
Basically built using advanced information and communication technologies (ICTs) including networks mobile devices, smart hardware devices, technologies of data storage and software applications.	[69]
A medium-sized technological community which is interconnected and sustainable, attractive, comfortable, and secure.	[70]
A penetration of smartness in urban context (cities) where focal domains (services and infrastructures) are made smarter by use of technologies.	[71]
Cities in which quality of life and services are enhanced by using digital technologies.	[72]
A city in which components of services and critical infrastructures use smart computing technologies.	[73]
A vision of urban development in which multiple ICT solutions are securely integrated for city's assets managements.	[74]
A city in which production and consumption of resources are optimised using advanced ICT.	[75]
A term used to cover how operation of a city, its efficiency and the quality of life of its citizen are Improved enabled by information and communication technology.	[76]

The effect of information and communication technology (ICT) when applied to issues related to environment, human capital through education, social and relational capital.	[77]
When information and communication technology is integrated in all aspect of human life, a network of sensors, real-time data and smart devices	[78]
Uses ICT to makes citizens more informed about what happens in the city and to allow a city to be more efficient and interactive.	[79]
They are modern cities in which are found all modern facilities and these cities are dependent on ICT.	[80]
They attempt to enhance urban performance through the use of information technology, information and data	[81]
It is a city is in which innovation based on technology is used in its development, planning and operation.	[82]

Table 2. 2 Definitions of smart city with 'people' perspective.

Definition	Reference
Community in which technology is extensively deployed as stimulus to conscious decision making and finding solutions business and social needs.	[83]
Cities that have the best quality of life and their citizens have the best economic wellbeing.	[84]
City that provide an environment to a community which is happy and healthy despite global challenging conditions and trends that might be brought by social, economic and environment.	[85]
Environment which prioritises human capital while developing innovative application by using digital collaboration.	[86]
Territories equipped with high potential of learning and innovation. They are developed though citizens' creativity and institution that build and manage knowledge and associated infrastructure.	[87]

Striving to make a living space which is more accessible, safe, competitive, profitable, open and transparent.	[57]
High productivity with knowledge –intensive workers, planning process which is output-output oriented and initiatives which valorises sustainability.	[88]
A high-performance urban framework in which, thanks to systems of information, people become more conscious of, and more integrated into city life.	[89]

Table 2. 3 Definitions of a smart city with ‘mixed’ perspectives

Definition	Reference
When a city combines economic, social and environmental growth, and when it interacts through a participatory government with democratic processes. It includes the introduction and deployment of ICT infrastructures to promote social and urban development by improving the economy, the participation of people and the effectiveness of government.	[90]
Product of knowledge-intensive and innovative approaches aimed at improving cities’ ecological, logistic, social-economic and competitive efficiency.	[91]
An ecosystem of urban innovation, a living laboratory that serves as an agent of change.	[92]
A city that has intellectual capacity to address many socio-economical and technical aspects of innovation development.	[93]
Has smart people in terms of educational degree, and the nature of their social interaction with respect to integration, public life and openness towards the wider world.	[94]
A city in which its infrastructures (highways, tunnels, railways, subways, major buildings, etc.) are tracked and integrated. It manages better its capital, schedules its maintenance and control security while at the same time optimizing services to its people.	[95]

Where investment in humans, social capital, modern information and communication technology infrastructure boost sustainable growth of economy and improve quality of life through participatory governance and wise management of natural resources.	[29]
Develops and manages a variety of creative services that provide information about all aspects of city life to all people through collaborative and internet-based solutions.	[96]
Links IT, physical, social, and business infrastructures to harness the city's collective intelligence.	[97]
A highly modern urban environment that serves businesses, organisations and, in particular, people's needs.	[98]
A city that perform well in governance, economy, people, living, environment and mobility.	[99]
A city that is run intelligently, sustainably and efficiently.	[61]
When actions taken with regards to management, technology, and policy includes risks and opportunities.	[100]
1) Uses innovative design paradigms to do something relevant to governance and economy, and 2) Is all about technology application in every area of human life (sensor networks, smart vehicles, information technology integration, etc.).	[101]
Aim to utilise advanced technology and information systems technologies to enhance all aspects of the city governance and quality of life for its residents, involve people and provide more efficient and resilient public services.	[102]
An integration of infrastructure and technology-mediated programs, social learning to enhance human infrastructure and structural change and people participation governance.	[103]

Definition of a smart city in the context of this research

In conclusion, analysis of definitions found in the literature showed that most of the definitions of the smart city concept focused on themes of interest while attempting to define it. A theme represented a perspective on which the concept was viewed which influences how the definition is selected. It was observed that almost all of them recognised technology as the main enabler of smart cities while at the same time some admitted that only technology could not make a city smart. Hence, it could be argued that every city was different and that the transition

from a contemporary city into a smart city was definitely different. A good example can be that major challenges of some cities, which could be the explosion of urban populations in Asian and African cities, could be a minor challenge for east European cities. Therefore, a route from city to smart city was different depending on the context and challenges to be addressed. This allowed to argue that a smart city is context sensitive and so should be its definition.
The context of this work focus on the information perspective of a smart, thus, a definition of a smart city in the context of this work would focus on information in an integrated system. As attempt to define a smart city the following definition is proposed:

"A smart city is system of systems which, enabled by technology, integrates information from all its subsystem to make them work together on a platform in order to facilitate decision making to decision makers and citizens by providing to them with the most complete and reliable information in real time".

2.2.3 The smart city concept evolution in time

The origin of the term smart city can be traced back in 1990s when advances in digital technology signalled ways forward for urban growth [1,29,104]. The term was as an alternative to traditional modes of planning where ICT and advanced technologies would enable finding solution to challenges faced by contemporary cities. The term smart city appeared in 1998 [58,105] and was first used in 1999 [15]. Before 2004, research and studies were focusing on only the technological perspective of smart cities, and it is only after 2012 that more work started to be interested in a holistic view of a smart city system [15]. It is since the introduction of IBM's smart world project that the concept of smart city started showing considerable interest [106]. USA became the first country to initiate a smart city initiative [107] and since then, interest in the concept of smart city has never stopped to grow. Later came the Digital Agenda for Europe established by the European Commission in 2010 with the main idea of promoting connectivity in Europe through basic broadband access to all in Europe by 2013 and fast broadband access to all by 2020 [108]. This Agenda encouraged smart cities in Europe and associated initiatives. In 2015 an initiative of an intelligent nations was announced by Singapore [109]. In the same year Japan announced the i-Japan initiative with a vision of creating an acceptable digital technology to the society which would lead digital innovation with which individuals and the society as a whole would benefit [110]. Among smart city initiatives are found in: Songdo and Busan (South Korea), Chicago (USA), Santander (Spain), Milton Keynes (UK), Masdar city (UAE), PlanIT Valley (Portugal) [1,15]. Many more projects can be found and the numbers have never stopped growing. In the developing world, rapid urbanisation is particularly fast and cities in developing countries are now following the smart city path [1,15].

It can be argued that the term has reached maturity point where detailed studies evaluate and highlight key issues. Many studies provide a timely and descriptive assessments of critical areas of application and what will be the future directions.

2.2.4 Enabling technologies of smart cities

Smart cities concept is definitely enabled by among others, information and communication technologies. Researchers emphasise on this and the literature shows that the idea of smart cities concept mostly build on technology. Various researchers presented technologies enabling smart cites: - [111] presented a model of smart cities which is based on data collected using CrowdSC technology. This is a technology that allows citizens of a city to contribute to its wellbeing. The technology allows people to contribute in decisions making concerning their city. The author presented this technology as a framework which allows users to collect data, make selection, and do an assessment of collected data. It is clear that such a model to be operational and accessible needs Wi-Fi to be made accessible to as many people as possible to generate data and people need to have smart phones or any other smart device. - [8] touch different dimensions of a smart city, from definitions of smart cities to data in smart cities, and from technologies used in smart cities to the proposed architectures of smart cities. The authors emphasise on the importance of data in realisation of smart cities and argue that smart cities rely on data, and later present an architecture of smart cities which is sourced by urban data, network data, and Internet of Things (IoT) data obtained from three different tools which are: GPS, RDFI, and sensors. - [72] proposes platforms to bring systems together and make a smart health system for monitoring health of elderly and disable person. Normally the health systems are made of sensors which are wearable by a patient and these sensors are powered by batteries. Here in the presented work the technology which is to enable the system is IoT with health sensing components. - [112] explores the progress of China's smart cities pilots in a report with the aim of better understanding the technologies used, the benefits and elements of smart cities. The authors argue that smart cities are based on IoT and are built on intelligent sensing technologies. They present technologies in smart cities which have IoT and cloud computing as their major enabling technologies. - [113] says that cities are so complex and articulates that cities of the future to be able to develop sustainably, they will need to adopt the smart cities concept. The author identifies cloud computing as enabling technology which is associated with other technologies to allow data collection for the cloud. - [114] explores the existing practices in traffic control systems and proposes a technique that uses sensing technologies and WiFi as enabling technologies which are to be incorporated in existing traffic control practices. The authors develop a technique and set it up to explain its functionality in a case study in Oulu, Finland. - [115], just like mentioned by other authors, finds it necessary to adopt the smart cities concept. The author admits that smart cities operate in a complex environment and proposes architecture which is enabled by semantic web technologies. The author argues that smart cities are based on IoT. Other technologies in the proposed architecture are 3G, LTE, and WiFi. - [116] emphasis is on data management. He admits that it is not easy to manage big data with conventional databases due to its complexity and points out the necessity to manage such big data where he proposes open data as solution to manage big data. The author mentions that data from all sources of technologies, including smart phone and GPS, would allow smart solution and therefore enable smart cities. - [117] investigate the process in which Barcelona is taking to transform into a smart city. For the case of smart Barcelona, two sources of data were identified by the authors: data from sensors and open data, and data from social media and Crowdsourcing. Hence, the main enabling technologies for smart Barcelona are sensor networks, WiFi network and crowdsourcing technology. - [101] presents a model that allows quick reaction on variety of events. The author gives a high level view of the concept of event driven smart city and its architecture. This concept of event driven smart city is enable by the IoT, internet of people, and internet of service which he explained. Other enabling technologies are Global Positioning System (GPS), Sensor networks, social media and web technologies. - [118] presents mobile health and smart cities, and introduces a concept of context-aware to complement mobile-health for smart cities. Normally, in m-health, the source of data is the patient but in s-health, the authors explain how data from patients can be useful for improving the city's behaviour towards its citizens. The enabling technologies for the context-aware concept are sensors, big data and the cloud, and internet technology. - [119] proposes a smart city architecture which technology wise is based on semantic web technologies. The functionality of the proposed architecture is explained and is enabled by technologies such as wireless sensors, smart phones through GSM/LTE 3G/4G, and IoT.

Internet of things (IoT)

The drive of our society looking for comfort and progress makes technology even more attractive. Internet of things has emerged and has gained popularity in the modern wireless telecommunication due to its capacity to address challenges the human kind faces. Internet of Things refers to products and objects which are interconnected through variety of things such as sensors, Radio-Frequency Identification, etc. to allow interaction among them. IoT is set to have high impact in many aspects of future daily life. For Smart Cities Concept, Internet of Things will be one of the main enabler technologies where many of the objects that surround us will be wired which will allow humans and object communication and objects to objects communication [120–123].

Cloud computing technology

Smart cities concept is most of the times referred as one that harness the power of data and collect data from all sources of information, process it into meaningful information, and make the information available to citizen to help them make informed decision, hence, improve quality of life of citizens. This requires a huge capacity of data storage to be able to store data of such magnitude and this is where cloud computing come in play. It uses a network of server remotely hosted on internet to manage, store, and process data. (see Mazza et al., 2014, Wei et al., 2014, Hashem et al., 2015)

Figure 2. 3 Cloud computing [124]

Mobile computing technology

Mobile devices are nothing like they were a decade ago. They have become sophisticated and very powerful with advanced computing. Smart phone can not only be used for calls and messages but can also be used to perform many functions of a computer. They are equipped with sophisticated sensors, they have the capability to access internet and have an operating system just like computers. They are increasingly becoming intelligent and are capable of sensing orientation, location, acceleration, and can record videos and audios. With their sensing capabilities, they can allow to store personal information, personal therapy, etc. Mobile computing has that capability to use technology wirelessly and access remotely stored information by using small and portable wireless devices with computing capabilities [125,125].

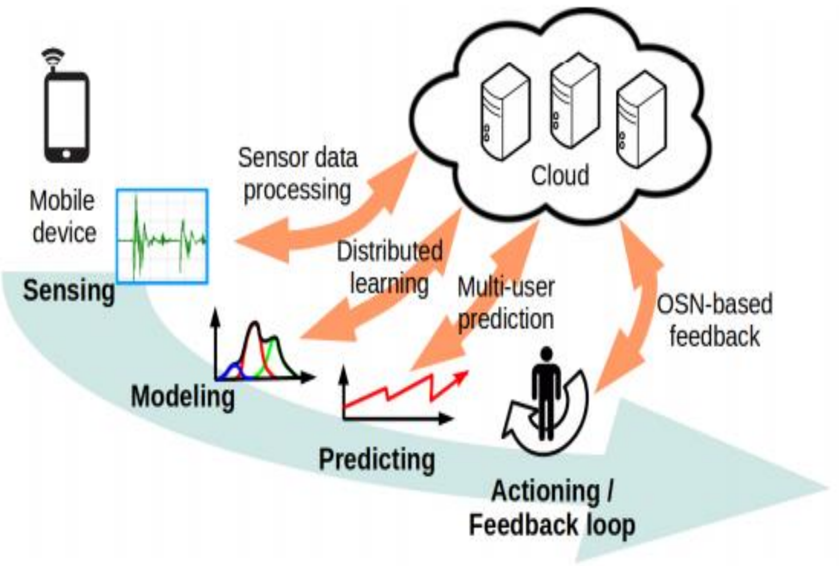

Figure 2. 4 Anticipatory mobile computing architecture [125]

Big data

Data has largely increased over the last two decades and the term big data is associated to manly the increase of global data and the term big data describes enormous datasets when compared to traditional datasets. It describes a large amount of data that need analysis. It also brings to surface understanding of various phenomenon and challenges. Big data has potential and many have invested in research about it and its applications [126,127]

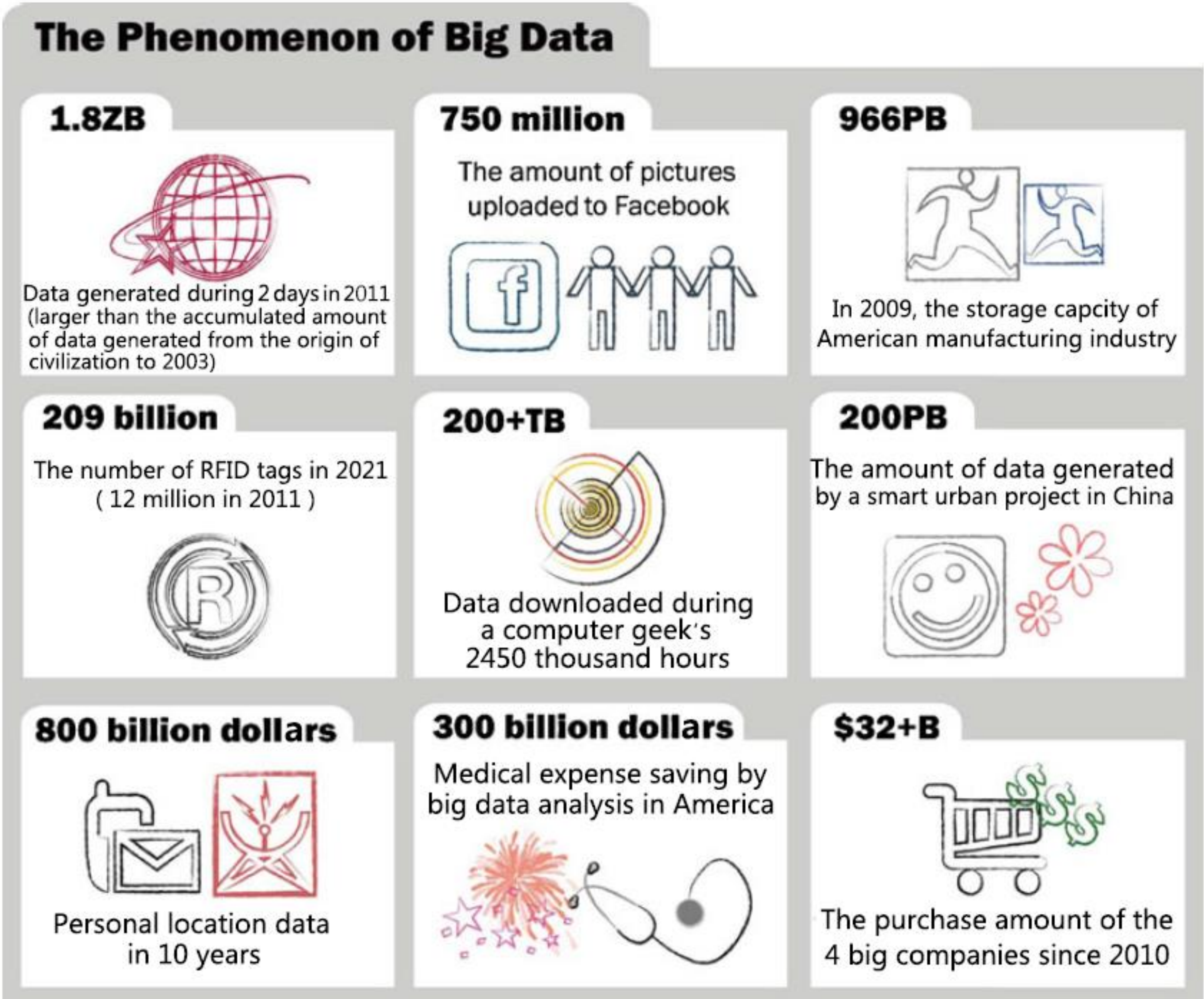

Figure 2. 5 The phenomenon of Big Data [126]

Crowdsourcing Technology

It is a development of the principle of outsourcing where the crowd (people in general or citizens) are given tasks as an open call soliciting their contribution which allows them to obtain needed services. These tasks are generally spread online and it is one of the modes of sourcing information from people who volunteer to contribute to achieve results [128,129]. It was argued that cloud sourcing has great health and service quality improvement among other benefits [130]

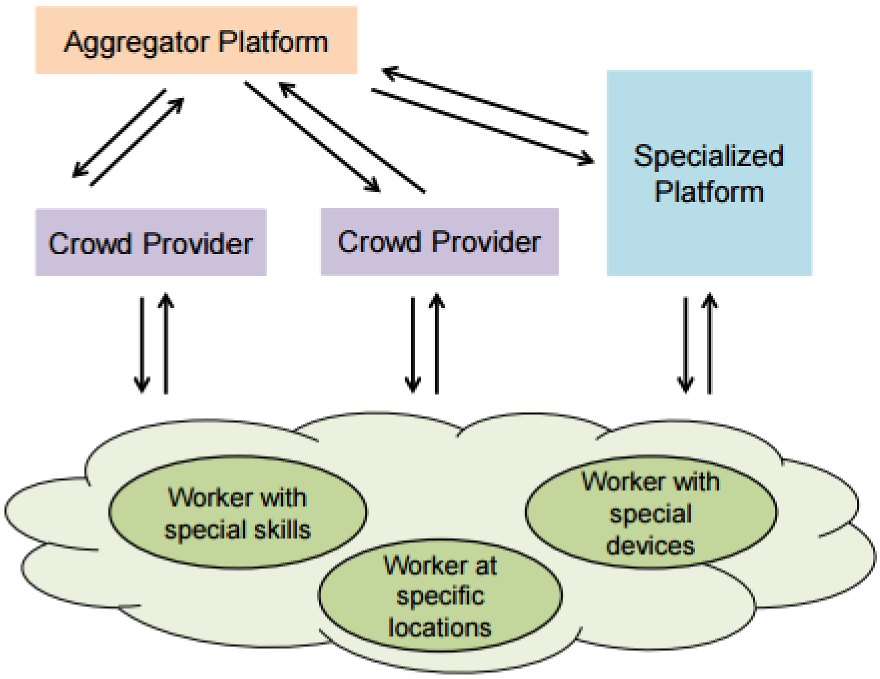

Figure 2. 6 Crowdsourcing types and their interactions [129]

Reflection:

A large number of research have been done trying to explain the smart city concept and propose a variety of potential technologies which can be applied on cities to deal with their challenges in the process of transformation into smart cities. Various enabling technologies are mentioned in the literature and every researcher presents technologies according to context in which his is doing his research. As complex as the smart cities concept is, findings show that there will be no limits to what technology to use or not use. Any useful and safe technology will be adopted as enabler of the smart cities as long it is acceptable and fulfil the requirement for such task.

2.2.5 Why the transition to smart cities? The potential of the smart city concept

As mentioned earlier in sub-section 2.1.1, rapid urbanisation generates challenges and issues, and it was shown later that the smart city concept is an opportunity to deal with these challenges and issues. Making reference to section 2.2.3, it can be deduced that many cities have embarked on the smart city path and have launched smart city projects to accommodate rapid urbanisation and urbanisation in general. A wide range of projects and studies have been launched over the las decades [33]. Analysis of definitions of the concept presented earlier in this chapter showed that technology is one of the main enabler of smart cities. In a work by [8] it was argued that the smart city concept arose from problems and challenges brought by rapid urbanisation, and that the revolution of ICT offered an opportunity of solving urbanisation challenges and issues under the umbrella of smart cities. The work in [8] was found consistent with [24,33] who confirmed that the vision of smart city was born to bring solution to challenges arising from rapid growth of urban population which is generally followed by rapid urbanisation. Among the observed benefits and potential of the smart city concept included: improve competitiveness of cities and minimize the issues related to tourism [33]; to be able to leverage assets such as information, technology, sustainability, culture, knowledge, etc. [131]; to improve quality of life in cities by solving dilemmas arising from urbanisation, speed up reduction of the cost of services and investment return, and to serve as catalyst for motivation to change [10,28]; to facilitate creation of skills for management, technical, governance, knowledge of design and innovation; to alleviate the ever growing strain on resources and urban infrastructure and provide a more competitive, efficient, sustainable, productive and transparent place to live [15] etc. The list could go on and on in the literature, and the smart city concept seems like a best fit solution to tackle challenges facing contemporary cities.

2.3 Subsystems of a smart city system

A smart city is a system of systems [26,32] and at the same time, a complex and multidisciplinary system [132]. This means that embarking in a transformation task of a city system is to deal with a complex system of systems. There has been many research and studies making effort to identify subsystems of a smart city [1,15]. In some work they were presented as components or dimensions [1] and in others as themes [15]. Whichever representation is adopted, a city system remains a system of systems. In this work, we sought to model an integrated system of a smart city. However, there is a necessity to identify subsystems that constitute a smart city system. Some other work stressed the necessity of an integrated smart city system [133,134], and since then, many researchers have worked trying to identify what should constitute a smart city system. Table 2.4 list some of the identified subsystems among many others that could be found in the literature.

Table 2. 4 Some identified subsystems of a smart city system (adapted from: [1])

Dimensions of a smart city system	**Reference**
IT education IT infrastructure IT economy Quality of life	[105]
Mobility Environment Economy Governance People	[99]
Technology economic development job growth increased quality of life	[83]
economic socio-political issues of the city economic-technical-social issues of the environment Interconnection instrumentation integration Applications Innovations	[71]
economic (GDP, sector strength, international transactions, foreign investment) human (talent, innovation, creativity, education) social (traditions, habits, religions, families) environmental (energy policies, waste and water management, landscape)	[64]

institutional (civic engagement, administrative authority, elections)	
human capital (e.g. skilled labour force) infrastructural capital (e.g. high-tech communication facilities) social capital (e.g. intense and open network linkages) entrepreneurial capital (e.g. creative and risk-taking business activities)	[91]
management and organizations Technology Governance built infrastructure natural environment	[27]
Governance Citizens Business Environment	[8]
Mobility living People Governance Environment Economy	[135]
Mobility living People Governance Environment	[136]

Economy	
Mobility Environment Administration Health Security Energy Offices and Residential Buildings Industries	[115]
Mobility living People Governance Environment Economy	[101]
Mobility living People Governance Environment Economy	[14]
Mobility living People Governance Economy Offices and Residential Buildings	[11]

Natural resources	
Mobility living People Governance Environment Economy	[99]
Mobility living People Governance Environment Economy	[137]
Mobility living People Governance Environment Economy	[24]
Smart Mobility Smart Living Smart Environment Smart Citizens / People Smart Governance Smart Economy Smart Architecture and Technology	[15]

Another detailed and more recent work by [15] provided a list of subsystems with a wider range of details. After a deep exploration of subsystems identified in many studies, it was observed that, since the work by [14] after [99], six subsystems stood out as the subsystems of a smart city system: smart governance, smart mobility, smart environment, smart people, smart living, smart economy. These six subsystem were discussed and explored where some authors referred to them with different terms such as axes, dimensions, components, themes, etc.

2.3.1 Smart mobility

The increased number of cars has created higher demand of road capacity than the existing supply and made it impossible to keep the cities moving. This high demand results in road network situations such as traffic congestions issues, increase of carbon emissions, parking space issues etc. [138]. Smart mobility mitigates present and future mobility related issues. It allows optimisation of transportation network by using intelligent systems. This subsystem of a smart city system brings functionality of infrastructure and services on a scalable and interoperable platform for a more optimal management of resources [99,139]. Smart mobility generally involves efficient transportation systems which make use of time and energy efficiently. It also involves transportation systems which use renewable energy rather than relying on fossil fuel, encourage and promote non-motorised transportation. Discussion on this subsystem has been mostly on intelligent transportation systems (ITS), application in the context of a smart city and traffic management [138]. Other interesting areas of discussion about smart mobility include the Internet of Vehicles (IoV), where its role is to make available applications to improve road safety [89,140], vehicle tracking in real time [141], and route stability through novel algorithms [142].

2.3.2 Smart living

Smart living is one of the six subsystems of a smart city system. It is about quality of life and is associates with culture, health, security and safety [14]. It includes healthcare, safety and security in urban environment, education and sustainable buildings that enhance living quality. Rapid urbanisation, which is normally preceded by rapid urban population growth, threatens the quality of life in cities, especially in developing countries. The growth of urban population in cites is followed by the growth of public service demand and as per the predictions [143,144]. Urban population will continue to growth which will decrease the quality of services offered to people. To be able to maintain and improve the quality of services for cities' inhabitants in general, smart living is the identified solution. The success of smart living is a factor of living conditions which are healthy and inclusive. Healthcare is an indicator of quality of life of people in a city and studies have been done in this line where they touched aspect like health of elderly, development of a framework of health management and real time health monitoring [72,145,146]. The work by [145] even proposed Big Data from healthcare. Safety and security in urban environment constitute a high concern as well and there has been studies trying to associate ICT with safety enhancement through a crowdsourcing model [82].

2.3.3 Smart people

Among the main aims of the smart city concept include to improve quality of life of people living in cities [90]. Smart city is all about serving people. Therefore, planning and designing smart cities need to substantially consider the 'people' perspective, among other perspectives, to insure improved service delivery to people [80,147]. Cities do not only reflect infrastructures, but first and foremost people. There is no way a city can be transformed into a smart city without smart people in the city. It is clear that one of the major issues that the smart city concept will address, urban population growth is at the forefront. Smart cities will be enabled by ICT and other enabling technologies and its people will need to have a certain level of skills, qualification, creativity, and willingness to adapt to intelligent way of doing thing to transform their cities. In [14] some characteristics that would characterise smart people were identified. The success of smart people will be determined by having skilled and educated citizens, who have willingness to participate in decision making process and present their opinion with regards to the development of their cities.

2.3.4 Smart governance

Governance of a city should be seen as being able to manage a city to allow sustainable urban development. With growth projections of the urban population, it is obvious that cities' governments are concerned with consequences that will be associated with this growth and the sustainable way to deal with expected challenges. Through smart governance, it is believed that sustainable management of cities will be possible in the future [14,148]. Smart governance constitute a major subsystem of a smart city system and enables other subsystems by good decisions, transparency, and good service provisions. Smart government is described as one which is transparent, which develop strategies in line with sustainable development, which value democracy, has efficient and interconnected governance [149,150]. It was observed that many of the recent work on the smart governance matter focused on open data and issues related to open governance [151–155].

2.3.5 Smart environment

Smart environment is an important subsystem of a smart city system. Smart environment considers many factors [14,71]. Smart environment means air quality with zero emissions, emission monitoring, water, management of waste, green spaces, green infrastructure development and monitoring, etc. [102,156–158]. To succeed in smart environment, there is a requirement of an urban development plan and good policies for resources management. There should also be strategies to encourage reduction of greenhouse gas emissions, efficient energy consumption to cut down pollution, preservation of environment through sustainable urban planning and embrace the use of modern technologies.

2.3.6 Smart economy

Smart economy, as subsystem of a smart city system englobes m-commerce and smart business [159,160]. [99] identified characteristics of smart economy: innovative spirit, economic image and trademarks, productivity, flexibility of labour market, international embeddedness, and the ability to transform. Smart economy should be one that allows optimisation of resource usage, develops policies that allow economic development, and it should be one that is sustainable and create job accessible to all, stop loss of jobs and address unemployment. The characteristics of a smart economy are to be able to enhance the quality of life in a city, attract and accommodate investor and be the economic engine of the smart city.

2.4 From contemporary city system into smart city system – Transformation approaches

Smart cities and their capabilities (see sub-section 2.2.4) made many cities around the word reflect on the large number of projects that could be implemented to improve cities by transforming them into smart cities. In this section, various approaches used to transform contemporary cities into smart cities were discussed.

2.4.1 Approaches of transformation from a city system into smart city system

We are in an era where the word "smart" is found almost everywhere: smart phones, smart television, smart grid, smart watches, smart cities, etc. and yet defining 'smart' is rather elusive [39]. The presence of many different definitions of the smart city system, numerous approaches trying to explain the process through which a city system can be made smart, and lack of a clear methodology through which a city system can be transformed show a need of more light on when a city labelled smart is really smart. A city system is extremely complex and multidisciplinary. Not understanding it can lead to criticism, to be considered as the outcome of vendors [132], and to question its efficiency [161]. Another work by [1] criticized transformation approaches of cities into smart cities and accused to be technology oriented instead of being more governance-oriented to endorse relations and social capital in urban environment. Transformation of a city system into a city system was said to be not an easy task [16] and required effort from different representatives such as political, inhabitants, administrators, entrepreneurs and various communities [131] . The process of transformation of such a complex system involved six subsystems (smart governance, smart mobility, smart environment, smart people, smart living and smart economy) [25]. The transformation process in a work by [16] was divided into four phases: organisation, planning, execution and measurement. Many more approaches of transformation could be found in the literature where some approaches were technology centric [28] and others endorses citizen-centric approaches and the main role allocated to stakeholders [20,162–164].

After analysis and observation on existing cities labelled smart cities, two main approaches of transformation could be identified: the first approach observed focused on transformation of existing cities into smart cities. This approach mostly relied on technology and infused technology into existing infrastructures and services to improve efficiency and the quality of services offered to its citizens. This is the case of cities like Barcelona, smart-Santander, Seoul, etc. The second main approach identified was to build a new smart city from scratch. In this second approach, technology was put forward in conception and notable cities are Masdar City (UAE), Songdo (Korea), and PlanIT Valley (Portugal).

2.5 How 'smart' is a 'smart city'?

Given that some work tried to make rankings of different smart cities around the world, some of smart cities are considered 'smarter' than others. In this section a review of literature was made with the objective of identifying what made a city smart. Later in this section, the research gap that motivated this research is exposed.

2.5.1 What makes a city smart?

The multidisciplinary characteristics of the smart city concept makes the task for finding what makes a city smart broad and no straight forward answer to that. Becoming a smart city was said to be fashionable which made many cities claim to be smart [131]. In [161], the efficiency of the smart city concept was questioned. However, findings in sub-section 2.2.4 put in light the potential of smart cities. Attempting to respond to the question, definitions of a smart city were found very informative. We saw that most of the definitions were showing that infrastructures for information and communication technology would make a city smart (see sub-section 2.2.2), but cities are aware that only technology cannot make a city smart, more is needed [16]. Existing research on the smart city concept showed that there were many initiatives carried out to transform existing cities into smart cities [1,15,16]. While many cities can now be labelled smart, an analysis by [16] of over 200 cities labelled as smart city revealed that all of them could not be classified as fully smart. They evaluated all those cities using a predefined classification of smart cities that considered three levels: fully, medium and low smart cities.

In conclusion, based on most of definitions, one can argue that technology plays a big role in the making of smart cities among many other factors. It was said in [165] that a city is smart if it is entirely equipped with ICT systems which serves its people. It wouldn't be wrong also to consider a definition by [99] that shows that what makes a city smart is the fact that it performs well in the six subsystems: governance, economy, people, living, environment and mobility. Many cities are enthusiastic to identify themselves as smart, but the size, scale and breadth of projects required for this transition is long and complex. The concept of smart city is still evolving, definitions of the concept and approaches are still being proposed and a lot work is still in progress trying to model a smart city system.

In this work, we put fourth integration and align with [99] to argue that what makes a city smart is to have all subsystems of a smart city system working together as whole on an integrated platform. It acts like a catalyst to enhance information and facilitate the smart city system to perform well in all the six smart subsystems.

2.5.2 Degree of smartness of a city

The word "smart" is complex and sometimes it can be confused or interchanged with "intelligence" [39]. However, while the word "smart" can be used to identify situations or circumstances which have been successfully addressed, "intelligence" comes inherently and is not necessarily connected to situations or circumstances reflecting challenges faced by cities such as traffic congestion, air pollution, waste management, etc. To take this further, while two cities can be smart, one can be smarter than the other based on efficient and intelligent solutions adopted to make life in a city easier and more pleasurable to the general public. To put this into perspective, a city is a system of interconnected subsystems [26] and cities around the world started the transformation process leading to smart city labelling [39], and from that, smart cities rankings [14]. To take the smart cities ranking a bit further, [166] ranked the top ten smartest cities in Europe. It was observed that there might be confusion between a smart project and a smart city. For example, calling a city smart because it invested in a project of intelligent street lighting or the use of Internet of Things (IoT) to improve waste management can lead to ambiguity and this bring back the question of what it takes for a city to be smart (see subsection 2.5.1). If smart cities can be ranked, it means that some cities can be smarter than others. Therefore, there is a need to identify at what degree a city can be identified as fully smart.

2.5.3 Ranking of smart cities based on degree of 'smartness'

To cope with the complexity of a city system in the process of transformation into smart cities, generally cities focus on one or two subsystems [26]. Research conducted by [23] evaluated which of the six subsystems [15] of a smart city system were given more importance based on a number of projects addressing a particular subsystem. Their findings showed that while there happened to be more projects on smart mobility and smart environment (see table 2.5), 'Smart Governance' was qualified as the most important followed by 'Smart People' and the least important was 'Smart Economy'. It was also believed in [16] that 'Governance' was the most importance as it was the one that led the coordination of all actions in the city such as development of planning strategies for city development and transformation of the six subsystems. However, transformation of only one or two subsystem and leaving the others untransformed does not make a city fully smart [16].

Table 2. 5 List of some smart city initiatives with their selected domain of focus [167]

Program	Economy	Economy and Environment	Energy	Energy and Environment	Environment	Environment and People	Environment, Energy	Governance	Lifestyle	Lifestyle, Environment	Mobility	Mobility and Environment	Mobility, Governance, Environment	Technology	People
AMSTERDAM			■												
MALMO		■	■		■			■	■		■				■
MALTA	■														
MASDA CITY			■		■			■			■				
PLAN IT							■	■			■				
SINGAPORE			■		■			■	■		■				
CURITIBA		■			■	■					■		■		
SONGDO				■	■						■			■	
TIANJIN					■				■	■		■			
YOKOHAMA			■		■										

In [16], after identifying transformation factors of a city, divided smart cities into three types. Low smart cities which address immediate problems but do not adhere to models and standards, Medium smart cities which put more efforts to use models and/or apply standards, and fully smart cities which comply with identified factors and phases throughout the process. Considering the naming of the latter type, it can be argued that though cities can be labelled "smart" based on project initiatives involving transformation of a city, only some of them can be labelled fully smart and others not fully smart. In the context of this research, such line of thought led to an observation of degree of smartness. Based on [99] who defined a smart city as one which perform very well in all six dimensions: smart economy, smart people, smart governance, smart mobility, and smart environment; the six subsystems of a city system needed to be fully transformed and well integrated before a particular city could be given a label of smart city. Six degrees of smartness could be derived from this line of thought, and hence, six designations with 1st degree smart city designating a fully smart city (see Table 2.6)

Table 2. 6 Degree of smartness of a smart city (SC)

Degree of smartness	Subsystems operation in smart conditions
1st degree	It is a full smart city system. The six subsystems of a SC system are operating in smart conditions.
2nd degree	Five subsystems of a SC systems are operating in smart conditions.
3rd degree	Four subsystems of a SC system are operation in smart conditions.

4th degree	Tree subsystems of a SC system are operation in smart conditions.
5th degree	Two subsystems of a SC system are operation in smart conditions.
6th degree	Only one subsystems of a SC systems is operating in smart conditions.

This means that a full smart city system is one that has all the six subsystems fully transformed into smart subsystems and very well integrated with all the other remaining five. In this case a city can be labelled "smart city". On the other hand, if only one subsystem is smart, then the city is smart but only at the 6th degree, which is the lowest degree of smartness.

2.5.4 Identification of the research gaps

During the past decades city systems has become more information-based and many changes have been occurring regarding the way people live in urban environments and the way cities are governed. Internet now constitutes a major part of people's lives and many attempts have been and are still being made to combine all aspects of the city systems into smart city systems. A smart city system is generally regarded by many as the process of making use of technology to deal with challenges in cities such as the need to improve social and ecological sustainability where all citizens have access to services and resources which meet the basics of human needs and where citizens can stay informed and connected in a safe urban environment. However, cities need to reconsider the paths which is being taken in the process of transforming their systems into smart city systems to avoid long run risks that may lead away from sustainability [168]. In [99], it was shown that a smart city is one which is well performing in six characteristics which are the six subsystems. However, findings of the work by [168] allowed to argue that reaching success in these six subsystems does not necessarily result in sustainable success. In [169] a system was described as set of elements which interact among themselves internally and with the external environment. IBM defined a smart city as one that integrates key information of core subsystems [97]. Stressing on integration of subsystems, many researchers have shown the necessity of an integrated smart city system [133,134,170]. Integration of all subsystems of a smart city system was found to be essential to allow flexibility and access to real time information which allowed quick reaction and timely decisions making. A city system cannot be smart if its subsystems are not integrated [170]. All subsystems of a city system together constitute a liveable and sustainable environment and need to be integrated

[33]. For instance, it was argued that integration of a city system was the only way to cope with unpredictability of the urban environment [171]. Nevertheless, observed approaches of transformation from a conventional city into a smart city system showed that most of the efforts focused on developing projects thematically [167] without taking into consideration of holistic/systematic view.

In brief, while it was suggested that researchers and practitioners must take a systematic approach to understand the smart city concept [45], lack of holistic and systematic view incited contrasting views and disconnection of the subsystems and compromised the systematic state of a city systems where, as indicated earlier in this section, has to have all its elements integrated and connected and working seamlessly together as a whole [99,169,172,173]. This motivated this research and stressed on interconnection through integration of subsystems of a smart city system, i.e. incorporating all generated data from both homogeneous and heterogeneous sources. The dynamic approach of management of the integration issues of smart city subsystems and generated data is to consider a unified platform [7]. The lack of such crucial unified platform created a need of a model for such a complex platform and a need for an effective approach to designing, modelling and validating such an integrated model. Until now, published research proposed architectures, methods and approaches that could allow transformation of conventional cities into smart cities' subsystems one by one but failed to give an integrated model of a smart system. This work generated a methodology to model such a standard platform and gave its visual semantic representation. It presented a model of an integrated smart city system that solve related issues such as interoperability and scalability. Through a case study, this work zooms into two smart mobility subsystem to give a visualisation of how interrelation between subsystems would function to enrich information that influence decision making.

2.6 Conclusion

In this chapter, literature reviews were carried out to allow a better understanding of the smart city concept. A smart city is regarded as a system of systems and this chapter explored the literature to find what motivated the concept, how it was defined, what the subsystems were, what made a city smart and what was challenging the process of transformation of a city system into a smart city system.

Exploring a perspective of contemporary city and its major challenges, it was observed that, while urbanisation greatly improved the living standards by making easy access to utility, education, etc., most of the existing challenges were exacerbated by rapid urban population which in turns caused rapid urbanisation to accommodate everyone. However, rapid urbanisation hindered sustainable and socio-economic development. This chapter explored studies and research to find out what were the challenges of cities and exposed the proposed solutions which mainly showed that the smart city concept was the best fit solution to tackle these issues and challenges.

The chapter found that the smart city concept emerged beginning of the 1990s, more than 2 decades ago, but researchers and practitioners in the domains are still trying to define the concept. This exposed the complexity of the smart city concept and showed that a lot more is still to be done.

It was observed that many analogous terms are being used as alternative to smart city which created confusion and ambiguities. This chapter explored most of these terms, identified and described the two most dominant (digital cities and intelligent cities), and shade the light on how they differ to smart city. It was shown that though all terms are sometimes used interchangeably to smart city, a smart city was more than a digital city, an intelligent city, a wired city or any other identified term. While most of other terms where mostly technology centric, the term “smart city” was found more inclusive and was not only about technology.

Before exploring what made a city smart and what were the processes of transformation of a city into a smart city, some of the existing definitions of the smart city concept were analysed and subsystems of a smart city system were identified. Definitions of the smart city concept were categorised into three groups depending on the perspective on which they focused while electing the definition: technology, human (people), and mixed perspectives. From analysis, it could be argued that every city was different and its transition from a contemporary city into a smart city was also different. A route from city system to smart city system was different depending on the context and challenges to be addressed. This allowed to argue that a smart city is context sensitive and so should be its definition.

The subsystems of a smart city system were identified after review and analysis of the literature. This task was carried on to allow, later in this thesis, to conceptualise an integrated smart city system in Chapter Three, develop a methodology to model and perform an initial test of the model in Chapter Four, and do a further test through a case study in Chapter Five. Subsystems of a smart city system were identified: smart governance, smart mobility, smart environment, smart people, smart living and smart economy. Thus, transformation of a city system into a smart city system meant transformation of these subsystems all together without losing sight of the systematic and integrative view.

It is with a systematic view of the city and existing transformation approaches that gap was identified. While a city is a system of systems, and smart city is supposed to be a system of systems as well. This chapter also tried to answer the question of what made a city smart. A lot work has been done by many researchers and practitioners to ranks smart cities around the world which was, in general, preceded by identifying factors to consider in the ranking exercise. Findings showed that there was a degree of smartness for each smart city (see Table 2.7). This meant that a full smart city system is one that has all the six subsystems fully transformed into smart subsystems and very well integrated. It was found later in this chapter that the existing process of transformation of a city system into a smart city systems lacked a holistic and systematic view which incited contrasting and disconnection of its subsystems. This exposed the gap to be filled by this research.

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CHAPTER 3

Smart city system conceptualisation: The Model Based Systems Engineering (MBSE) approach

Chapter Two of this thesis showed that city systems were segmented and their subsystems disconnected as a way of coping with complexity while transforming them into smart city systems. This chapter applied a system engineering approach and presented an initial conceptual model of an integrated smart city system. A Model-Based Systems Engineering (MBSE) methodology together with systems modelling language (SysML), was used as the best fit method to cope with complexity while keeping the city system integrated and holistic. This chapter defines and describes the systems engineering (SE) approach, MBSE methodology and SysML applied in the initial conceptualisation process of an integrated model of a smart city system.

3.1 Introduction

Cities are complex and multidisciplinary systems of systems [132] and handling the process of transformation of such a systems is very challenging. The fact that the city systems involve multiple stakeholders and large information add extra constraints to their transformation process, from contemporary city systems into smart city systems. Previous work showed that, while all subsystems of city systems were supposed to be well integrated, most of the existing transformation approaches fragmented and disconnected the city systems as a way to deal with complexity [167]. By adopting the system engineering (SE) approach and with the principles of model-based systems engineering (MBSE), complexity of systems can be managed without fragmentations and disconnections [174]. Systems modelling language (SysML), a visual modelling language developed based a unified modelling language (UML) by the object management group (OMG), aids in the realisation of many intended purposes of MBSE which manly include: communication improvement among stakeholders, modelling complex systems correctly, consistently and completely through the systems engineering (SE) processes.

This chapter presents a systems engineering approach to assist cope with challenges associated to complexity of a city systems and lack of an integrative approach of a smart city system. In particular, this chapter focus on description of the approach, methods and tools, define them and presents an initial conceptualisation of a smart city system.

3.2 Background - approaches and practices

Over the past decades, the smart city concept has been evolving and different work has been done attempting to create the smartest city system. Numerous architectures have been created for different cities were cities chose areas of interest(s) and developed them into smart cities. What is notable is that deployed approached of transformation focus on some particular areas and connection and interrelation of all the subsystems of a smart city is not given special attention. If some examples of smart cities can be mentioned [175]: Bilbao (Spain) focused on smart people, smart environment and smart Governance; Bristol focused communication technology to set a foundation of smart city initiatives; Cape Town showed more interest in smart people; Copenhagen focused on smart environment and its connection to other areas such as mobility, people, ; Fujisawa (Japan) focused on environment, governance and people, Stockholm focused on creation of a smart and connected city with special focus on smart governance and smart mobility; etc. All these cities presented more or less the same approach of transformation. They developed projects in the framework of smart city focusing on particular subsystem(s). The review of literature also shows a variety of research works focusing on smart city implementation architectures, and among them:

- [176] present a smart city pyramid with five layers namely smart infrastructure, smart database resources, smart building management system, smart interface, and then smart city. The authors believe the proposed pyramid allow an enhanced system that would help controlling, monitoring and managing smart cities. Later, the authors present a platform which based on GIS and which is helped by GPS reference network for smart city business and application and management architecture. This allows a single management of the system across many sub-systems. However, the proposed architecture is representing components management of a smart city and does not give a clear and integrated model smart system of a city or architecture which gives structure and clear functionality of an integrated system.

- [24] proposed a platform based on Content Centric Networking paradigm (CCN). The authors mention that the reason they base their platform on CNN is that it can embrace easily existing and upcoming wireless technologies and allow securing application in different domains. The authors described the proposed architecture in details and give example with the use of use-cases. It is worth noting that the presented architecture does not show how all sub-systems in smart city can be brought together on one platform to form an integrated system which source information or data from all sub-systems and make it available for each and every single subsystem of the smart city system.

- [177] presents architecture of smart city through a perspective of mobile technology. He argues that smart phones are embedded with sensors which would allow them to be crucial elements of the future networked infrastructure. The author presents fundamental requirement that would enable smart cities: To largely instrument city's infrastructure, large-scale deployment of high-speed network infrastructure and efficient management of the aggregated smart data. The architecture is again found short in representing a smart city system as it does not give much about the system structure, integration and full functionality.

- [93] presents a reference model defining lay out of smart cities. The presented model is made up of six layers which the author describes. He later presents case studies done on three different cities in Europe: Barcelona, Amsterdam, and Edinburgh and evaluate their model with the presented reference model. His work addresses the city planning process toward smartness and presents priorities into reference model which could be used by planners in the process of defining smart city layout. Again, the presented model present does not give much on how to present clear integration of a smart city system and a clear understanding of smart city structure and functionalities.

- [68] present architecture of smart cities which they consider as representative information centric services and which they apply on nine domains (which can be seen as subsystems). Authors use "use-cases" as well to describe the architecture. A platform is presented within which services execution in smart cities are performed in three phases: discovery, security initialisation, and service usage. The authors extend significantly their detailing on how services in smart cities through NDN (Named Data Network) oriented platform can be handled in urban environment. However, the presented architecture fails to provide a semantic presentation of flow of information from the source to the end user and fail to present the main architecture of the proposed platform as an integrated system representing a system and prefer to present sub-systems individually using use-cases.

Considering the ICT perspective, [175] identified the most common architectures of smart cities which they argued to be differentiated by how layers acquire, process and use data. The authors presented projects in which the architectures were applied on different levels within one or more subsystems of a smart city system. Analysis by [178] conclude that, though some promising initiative exists, the notion of smart city is yet to be adequately modelled. Different approaches are adopted to conceptualise smart cities and cities like Amsterdam, Brisbane, San Francisco, etc. adopted the model of smart city which is relatively small-scale in general, and a more consolidated smart city approach was shown to be a necessary [178]. [179] conducted a bibliometric analysis and found that: (1) though the smart city research lacked cohesion, European universities supported the holistic perspectives; (2) existing approaches were mostly techno-centric. The authors further exposed the double, triple and quadruple-helix of collaboration as approaches adopter by various cities in the transformation process. [180] presented an evaluation framework - a multi-agent systems modelling approach where the goal was to do an evaluation to weather the proposed solutions where useful and beneficial for cities. Other approaches adopted by cities include to-down and bottom-up where for the earlier approach, strategies and frameworks are developed by the government and for the later has grassroots movements and put citizens in direct involvement.

All the above mentioned approaches of transformation target specific challenges among many contemporary cities are facing. Knowing that a city is a system of systems, the observed issue of lack of interrelation and connection of subsystems of a smart city and lack of a systemic view of city systems presents a significant gap that need to be filled, and the next section presents a new approach, a systems engineering approach to fill this gap.

3.3 The systems engineering (SE) approach

To solve a systems problem, one must grasp the fundamentals of the system, the objectives of the of the system, and the overall requirements and problems of the system [181]. Since its introduction, SE has become a distinctive discipline and a lot of progress has been made in this field [174]. It has been used in industries for decades, in defence, aerospace, etc. While traditional SE dealt with single complex problem to optimise systems performance, currently, SE does more such as life-cycle based approaches interpretation, systems and non-systems thinking, etc. [182]. Understanding the system engineering process will guide to its application in the context of a smart cites; a SE approach to achieve integrated smart city systems after transformation of contemporary city systems. Surely, discussion on the process of systems engineering goes in pair with SE models. Complexity can lead to unexpected territories if not well managed. SE help to manage complexity and facilitate continuous improvement, requirement discovery, properties and behaviours of the systems [183]. Definition of SE is a starting point to understanding the SE process and MBSE methodology.

3.3.1 SE historic background

It is with World War II that was realised the importance of management and synchronisation of complex systems to reach targeted long-terms objectives [174]. While before World War II military equipment's and weapons were not as complex as during and after, it is during and after WWII that SE evolved as a solution to complexity of the newly emerging processes and systems [184] and continued to develop by adopting different disciplines [185]. Rapid advancement in the technology field with special focus on systems of communication, space management, power distribution and space engineering took place around the 1930's and 1940's. Other areas of focus included telephone and radio and television industry initiated around the late 1930's as modern communications network as we know it today [174] and aircraft communication service around 1943 [186].

In 1950, formal SE teaching was initiated at the Massachusetts Institute of Technology (MIT) [187]. It was first formalised by Schlager (1956) who outlined the SE process by encompassing analysis, planning, optimisation, integration and testing [188]. The a first basic definition was provided in 1957 [189].

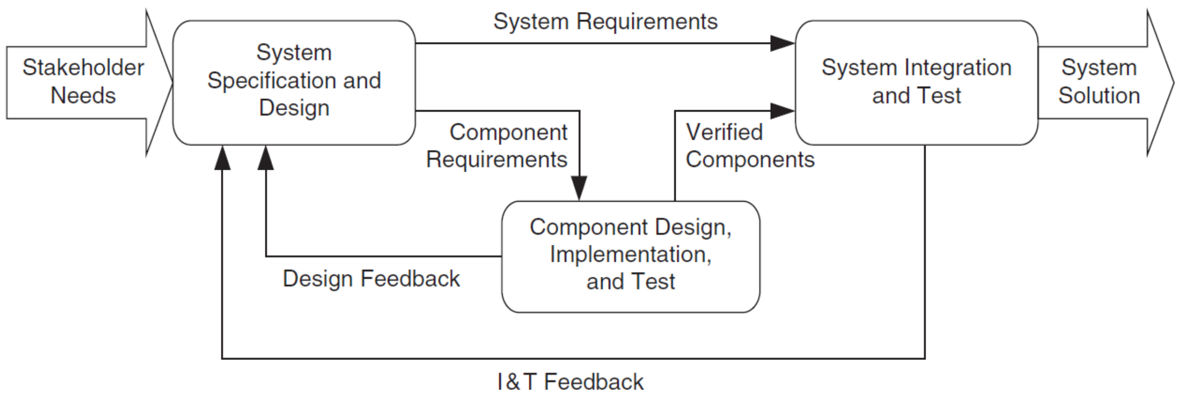

Figure 3. 1 A simplified SE technical processes (Source: [169])

It is believed that around 1954, Olthuis first introduced and advocated the idea of a holistic perspective [190]. SE has shown rapid advances due to increasing complexity, sophistication and diversification of systems in all aspects of the modern life.

3.3.2 SE definition and models

Unlike other conventional engineering fields, SE does not have fixed and predefined basic theorems related to science and physical properties. It was developed as a set of methods to address complex and unstructured problems within particular contexts and circumstances [174]. Many research and studies investigated and tempted to define SE from different perspectives and under established objectives. Sailor (1990) described SE as techniques and management processes capable to transform needs of customers into desired systems [174]. It was also define by [191] as *"The application of the system analysis and design process, and the integration and verification process to the logical sequence of the technical aspect of the project's life-cycle"*. In [192] SE was defined as a process of managing technology which included an order of operations related to customer needs to be transformed into system design after: allocating requirements, identifying design concept, design and integration consideration and testing. While these definitions introduced a description of SE terms like management and interdisciplinary, it was written in [193] that SE used a repetitive series of steps to insure quality of the system. In [194] SE was simply defined as *"the art and science of creating systems"*. Several other descriptions and definitions of SE could be found in the literature where some focused on a the perspective of multidisciplinary [195], and others focused on the information perspective [196] and problem solving [197,198].

What was observed about definitions was that SE is an interdisciplinary approach which is there to deal with complex problems of stakeholders and identify requirements which are used to design systems. This was found consistent with a comprehensive definition given by the International Council of Systems Engineering (INCOSE) [174]. It is in 1990 that, INCOSE, a non-profit organisation, was established to facilitate dissemination of SE practices, values and better solutions to societal and technical complex challenges. INCOSE defined SE as an interdisciplinary approach that allows to realise successful systems; a technique or a set of best practices to manage circumstantial complex problems. Four processes of SE were described in [183]: comprehensive (considering the system an integrated whole), iterative, logical sequence of processes and activities and transformation of operational needs into a form of parameters and preferred configurations.

Several models of SE could be found in the literature. Among them, lifecycle models which provide lifecycle development templates. Notable examples are Boehme's Spiral Model [199], Royce’s Waterfall Model [200] and Forsberg and Mood’s “Vee” Model [191,201] (see Figure 3.1).

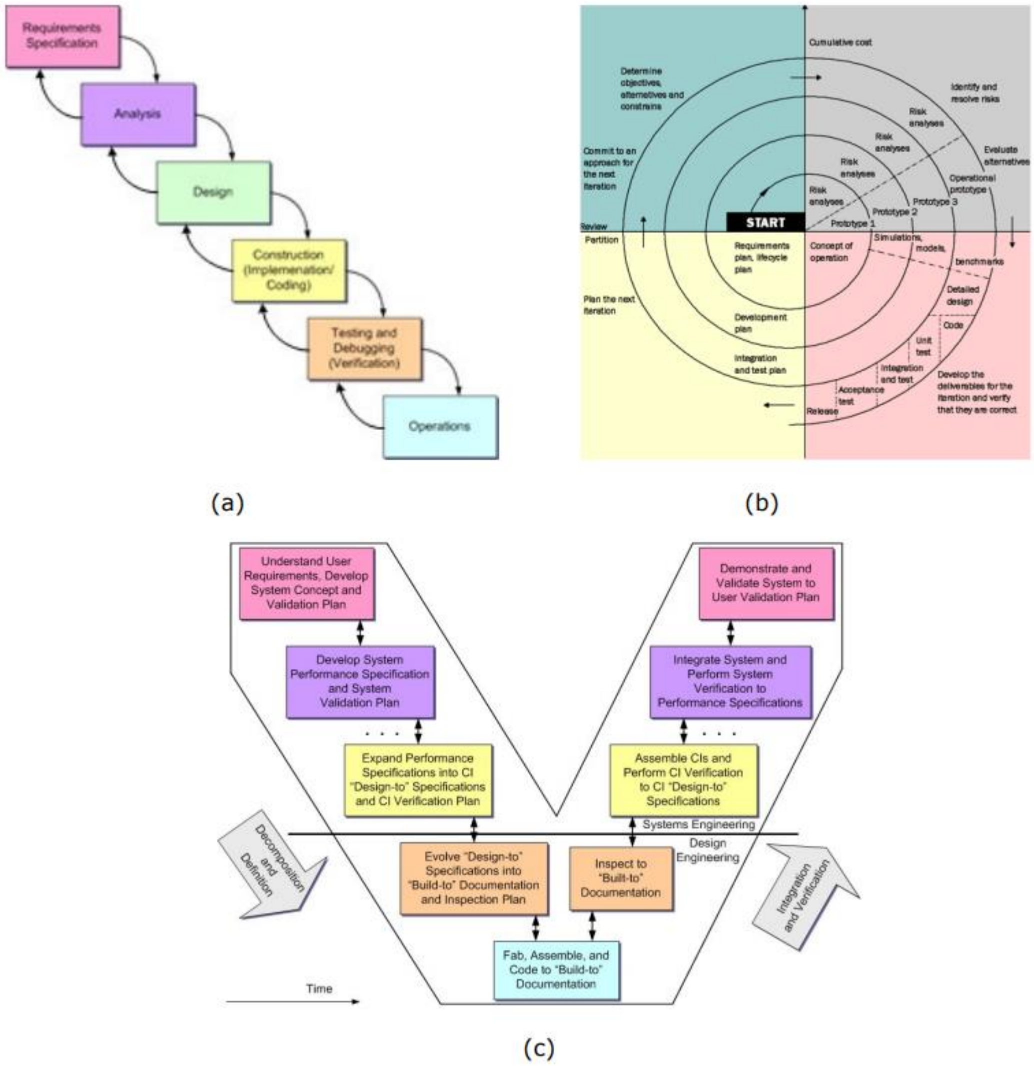

Figure 3. 2 SE lifecycle model: (a) Waterfall, (b) Spiral, (c) “Vee”

3.4 Model Based Systems Engineering (MBSE) methodology

3.4.1 MBSE historic background and definition

Systems continue to grow in size and complexity. Pioneers in the field of engineering such IBM, INCOSE and Vitech developed the MBSE methodologies to cope with the observed complexity, to assure consistency and traceability during the development process of systems. The term MBSE was first adopted by Wymore in 1993 and has since continued to mature and get more widely used [202]. It originated from the need to capture the system’s functionalities as a whole rather than disconnected considerations [203]. Various MBSE definitions were found in the literature where it mostly viewed it as a formalised and interdisciplinary approach to allow realisation of successful systems. For example MBSE was defined in [204] as a formal modelling application to facilitate the determination of systems requirements and assist the design, analysis, verification and validation throughout the conception, development and even latter after. Another definition in [205] showed almost the same description of MBSE and gave a more detailed definition: *"the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases"*. In [202], MBSE was described with a holistic view and was said to be a systems engineering approach built on system model to provide the real truth about systems.

What was observed was that the advantage of having MBSE was to have all information related to particular systems stored and managed in a way that allows interconnection of all model element and of cause all sub-systems of a system. In this case, the system development is more efficient due to automatic track of changes and identification of errors. More of the motivations of MBSE are presented in the next sub-section.

3.4.2 MBSE motivation

Many methodologies were developed in the MBSE field. Before diving into the most popular methodologies and exposing them, it would be more logical to fist discuss what motivate MBSE. According to how MBSE is defined, it can be argued that it facilitate management of systems complexities. It was also shown that while document-centric design could lead to errors and complications in systems management, model-based approach provided an environment that supported systems development for analysis, design, evaluation, verification of requirements and consistent checking [206]. Other observed reasons that motivated MBSE were to overcome deficiencies and practices affecting systems design and architecture [202], facilitation observed systems integration challenges [207], reduced the amount of time of information searching and assembling reports [208,209], optimisation of cost and quality and cope with high increase in systems requirements and their management [209]. Other MBSE motivations are: to cope with challenges related to disconnection of information within systems; to avoid difficulties related to document-centric approach for information management; to facilitate collaboration among individuals and teams from different disciplines for systems development; to bring solutions to communication issues; and for dealing with systems with multiple stakeholders, etc. [202].

In conclusion, MBSE offers advantages and benefits to systems engineers such as easy traceability, information management, and improved collaboration among teams from different backgrounds, automation in configuration and management and support different methodologies. In brief, it allows to deal efficiently with systems complexities and offers support during the entire life cycle of systems.

3.4.3 MBSE methodologies

MBSE is an approach that requires methodology, a set of process, tools and environment in which it can implemented [210]. For a better understanding in this context; methods, processes and tools were described in [211]: while processes represents objectives achieved by performing tasks in a logical sequence, methods are techniques used to perform those tasks and tools are instruments applied to particular methods that have the capability to enhance efficiency to perform the tasks, provided that the tools are applied with someone with proper skills. In an article by [212] on fundamentals of principles of good design, it was argued that the nature of MBSE depends on the use of proper and formal models to a particular domain. MBSE plays an important role in SE, and based on the International Council on Systems Engineering and a research by [211], six methods could be identified: IBM harmony for systems engineering, INCOSE Object-Oriented Systems Engineering Method, Vitech Model-Based Systems Engineering Methodology, NASA Jet Propulsion Lab State Analysis, Dori Object-Process Methodology and Weilkiends Systems Modelling Process. In [204,210], four methods were identified with special attention given to INCOSE Object-Oriented Systems Engineering Method (OOSEM). The description of OOSEM showed that it eased integration and supported object oriented concepts for more flexible and scalable systems which are capable to adapt to advances of technology and changing requirements. Figure 3.3 presents the foundation of OOSEM and Figure 3.4 illustrates how it leverages SE processes. OOSEM has development activities which are consistent with the “Vee” process (see Figure 3.2).

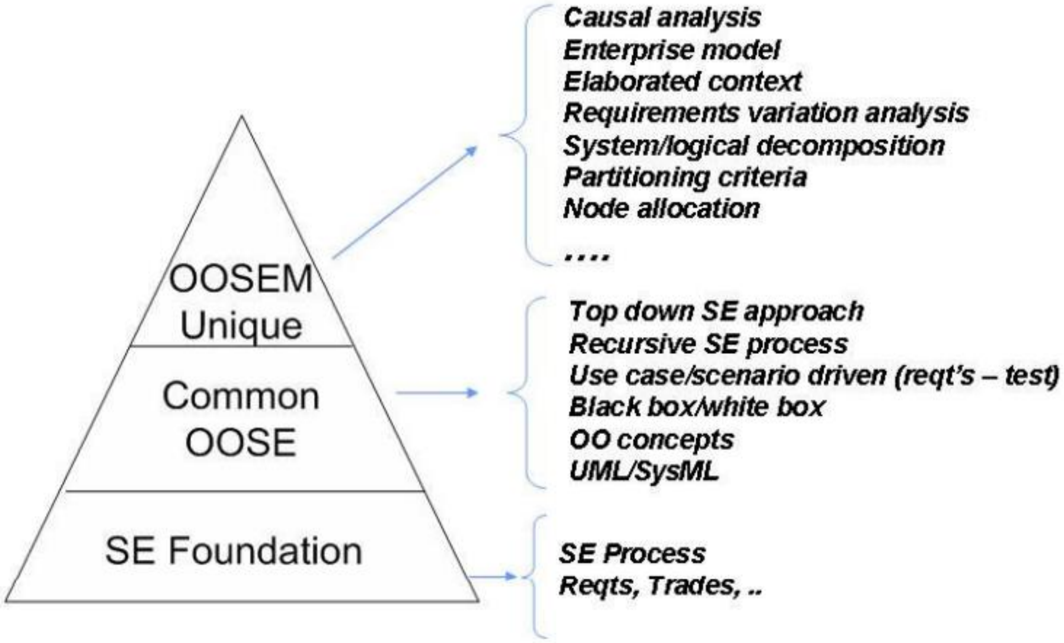

Figure 3. 3 OOSM foundation (source: [211])

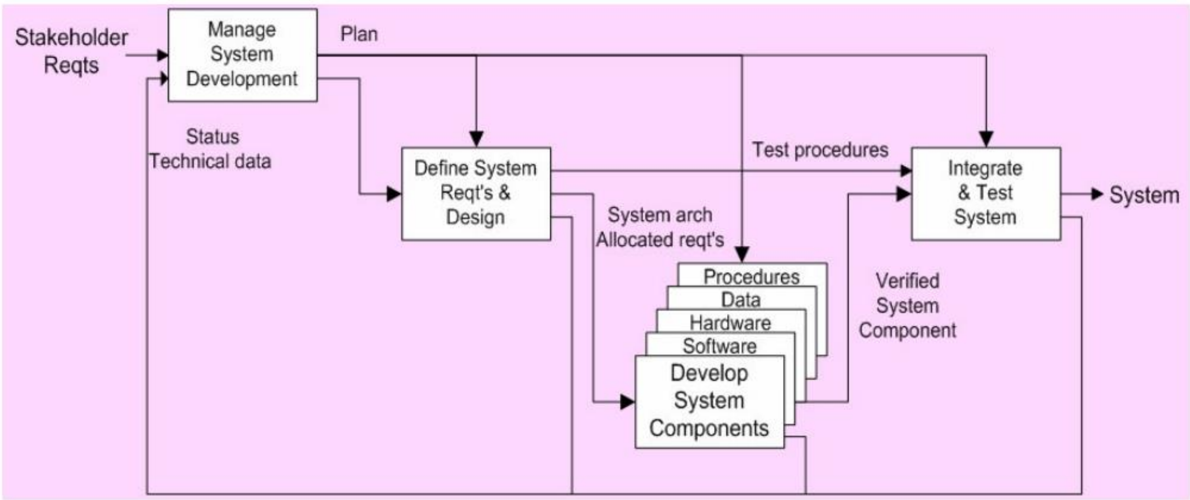

Figure 3. 4 OOSEM in the context of Systems engineering (source: [211]).

OOSEM makes use of the model-based approach and integrates the OMG SysML top down approach. To achieve the objectives in this thesis, OOSEM, which commonly uses Systems Modelling Language (SysML) developed by OMG, was chosen due to its ability to use full potential of MBSE approach.

While a lot have been done, more work is still being carried out in MBSE to improved collaboration, integration and modelling languages and tools.

3.5 Modelling tools - Systems Modelling Language (SysML)

SE has developed various tools and methods to facilitate management of various forms of complexity. To be able to deal with large and complex systems and system of systems, interdisciplinary teams needed to speak the same language that would enable MBSE and improve communication [210]. Thus, the OMG's SysML were developed.

3.5.1 SysML definition and background

While UML was said to lack characteristics of SE, INCOSE and OMG joint effort developed SysML. Though UML and OMG SysML are intended to complement each other, SysML is a results of UML customisation, specifically UML 2.0 (see Figure 3.4) to support SE analysis, specification, design and verification of complex systems [169,211]. Here is how SysML was defined by [169]: *"it is a general-purpose graphical modelling language for representing systems that may include combinations of hardware, software, data, people, facilities, and natural objects"*.

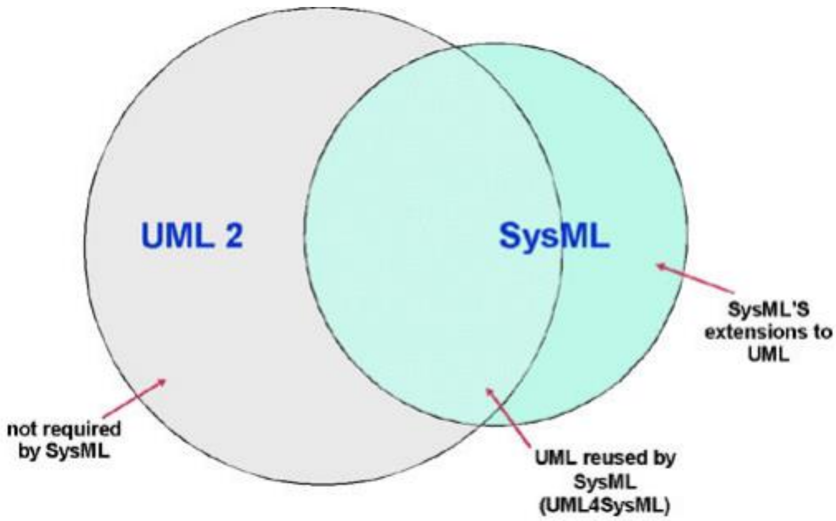

Figure 3.5 Relationship between UML 2.0 and OMG SysML

SysML and UML are not software or methodologies but visual modelling languages. MBSE incorporate these two as part of the methodology and facilitate lifecycle development activities and unambiguous communication. SysML provide a graphical representation and support design and analysis for SE.

3.5.2 SysML overview and SysML modelling tool

As mentioned earlier, SysML is a general purpose and graphical modelling language. It provides a working framework that allow to maximise capture of information of systems and enables to view the system model form multiple perspectives. It strives to satisfy all the mentioned goals in its definition, and to do so, various diagrams, specifically block definition diagram, requirement diagram, state machine diagram, activity diagram, parametric diagram and package diagram allow to accomplish the set goals.

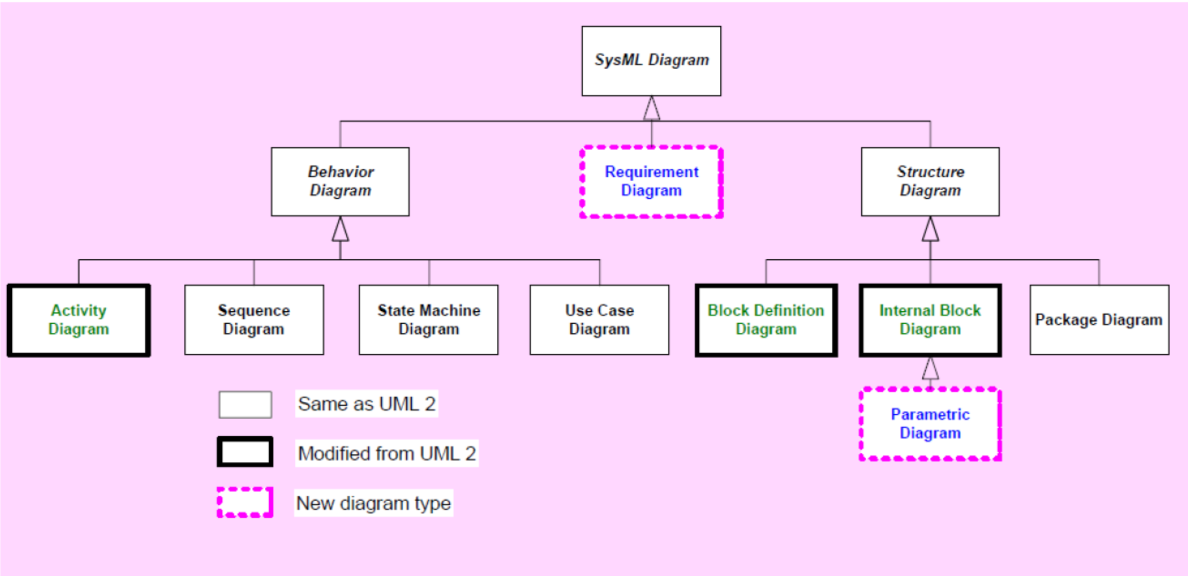

Figure 3.6 SysML diagram taxonomy and SysML –UML relationship

The major benefits of SysML [169] include:

- Gives a possibility to have multiple views which is very important for a complex system, especially when describing it for different audiences and different purposes
- It uses a standardised language which makes the symbols used for all the diagram being unambiguous to readers no matter diagram is being looked at.
- It has consistent views which can automatically update changes for all views
- It enforces consistency and can prevent any attempt to make incompatible connections
- It improves precision and efficiency in communications
- It provides a problem solving structure which is scalable

- It can better manage challenges related to size and complexity
- It is able to detect errors or any omission in early stage of systems development

SyML provides users with different types of diagrams, which can be classified into two main groups in addition to requirement diagram: behavioural and structural diagrams (see Figure 3.6). SysML advantage over UML is that it can use requirement diagrams to capture performance, functional, and interface requirements and it can also use parametric diagram do define with precision quantitative and performance constraints. Requirements are conditions to be satisfied by the system. SysML requirement diagram (req) specifies all the requirements, relationship to other model and allow traceability and verification.

Below is a short description of SysML diagrams:

- ❖ For structure view: block definition diagram (bdd) to define components, connectors, data and ports; internal block diagram (ibd) to define internal configurations and how they are combined. Other diagrams are package diagram (pkg) to show relationships among packages and what they contain, and facilitate organisation of elements; and parametric diagram (par) to deal with mathematical rules and parameters (constraints).
- ❖ For behaviour view: Activity diagram (act) uses control flow to specify systems dynamic behaviour; state machine diagram (smd) specifies system's dynamic for time-critical, safety-critical, mission-critical or financially-critical. Other diagrams include sequence diagrams (seq) to specify interaction via sequence messages and use case diagram (uc) to specify high level view of system transaction and external users.

While SysML is a powerful modelling language which has a capability to model a wide range of systems, it also requires a robust environment to run analysis and check model consistency. Keeping in mind that one of the major objectives on this work was to develop a methodology to model of an integrated smart city system. The methodology is presented in the next chapter where MBSE was complemented by SysML, a standard and general-purpose modelling language that benefited the development of the model by it capability to support specification analysis, design, verification, validation of a systems of systems, visualise complex systems and manage complexity. There is a variety of SysML tools which can be either commercial, free open source, or academic version. The Enterprise edition of Cameo Systems Modeller was found the best fit this research. It is a leading cross-platform collaborative MBSE environment which gives robust, smart and intuitive tools to verify requirement and track progress, define and visualise all systems' aspects.

3.6 Initial concept of a smart city system: The SE approach

As per its definitions, it can be argued that the smart city concept aims to improve life of citizens in all aspects. Chapter Two of this thesis showed that the smart cities concept can be embraced either by building a new city from scratch or by transformation of existing cities, which is the case of most of cities around the world. It was also shown that a city is a large, multidisciplinary and complex system. This means that its transformation requires appropriate systematic approach capable to deal with complexity. MBSE was found to be a very good fit to cope with complexity and perform transformation of cities in an integrative manner without fragmenting the city system. It is with a systematic view that a holistic and integrative conceptualisation of a smart city system is presented. The information perspective of a city system in put forward and a standard platform is conceptualised.

To achieve the transformation of a system, systems engineering approach was used (see section 3.2). The structure of the proposed holistic model of a smart city system is illustrated on Figure 3.7. The presented structure shows illustration at a high level and not the details of the model. On the presented structure, all the identified subsystems of a smart city system are brought together on an integrated platform. The structure shows that all the smart subsystems are connected through a standard platform which integrates them and make them operate together as connected parts of smart city systems. The operations at the platform level are illustrated on Figure 3.8. The figure presents the subsystems as parts of a smart city system in which data blocks source data produced by different sources of information from different subsystems and process it into useful information. Three stages can be observed: - 1st Data is gathered from external sources by each individual subsystem of the six subsystems of a smart city system and stored on the data platform. - 2nd, it is at this level where processing of data is done to extract meaningful and useful information from data. The processing of data at the data block level produce information which is stored at the information block level. - 3rd, integration of information produced from processing data. At the information block level is stored all information from all subsystems. It is from there that information is made available to all.

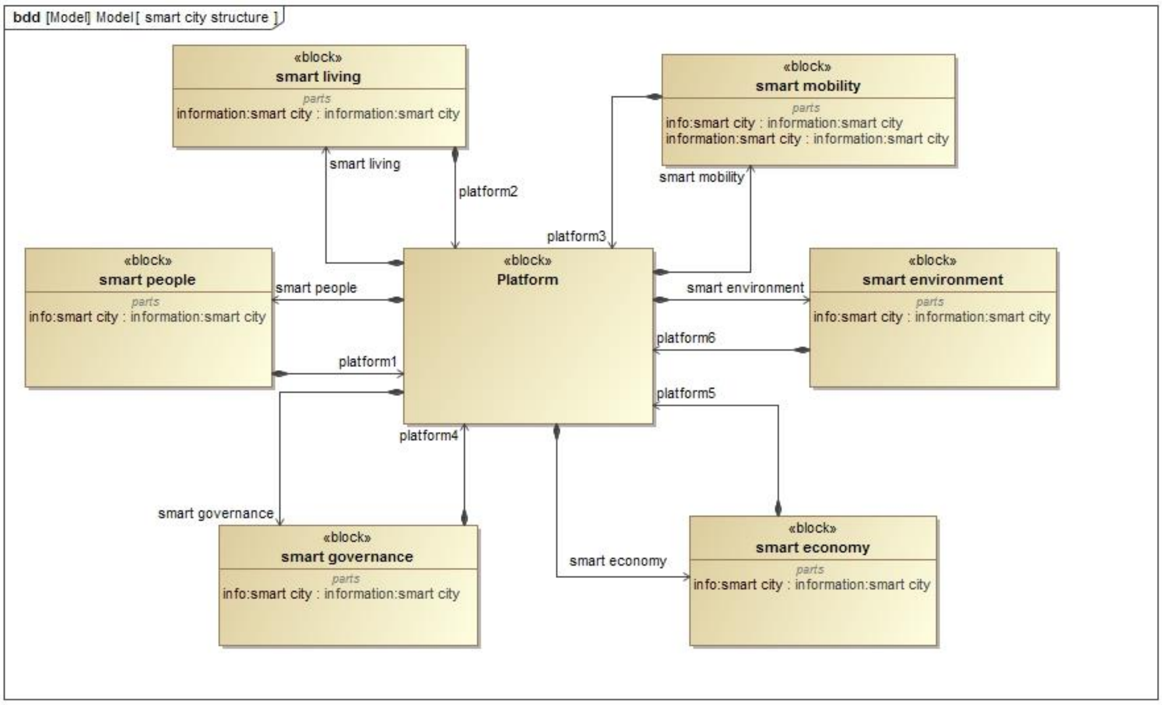

Figure 3. 7 High level structure of the proposed smart city system

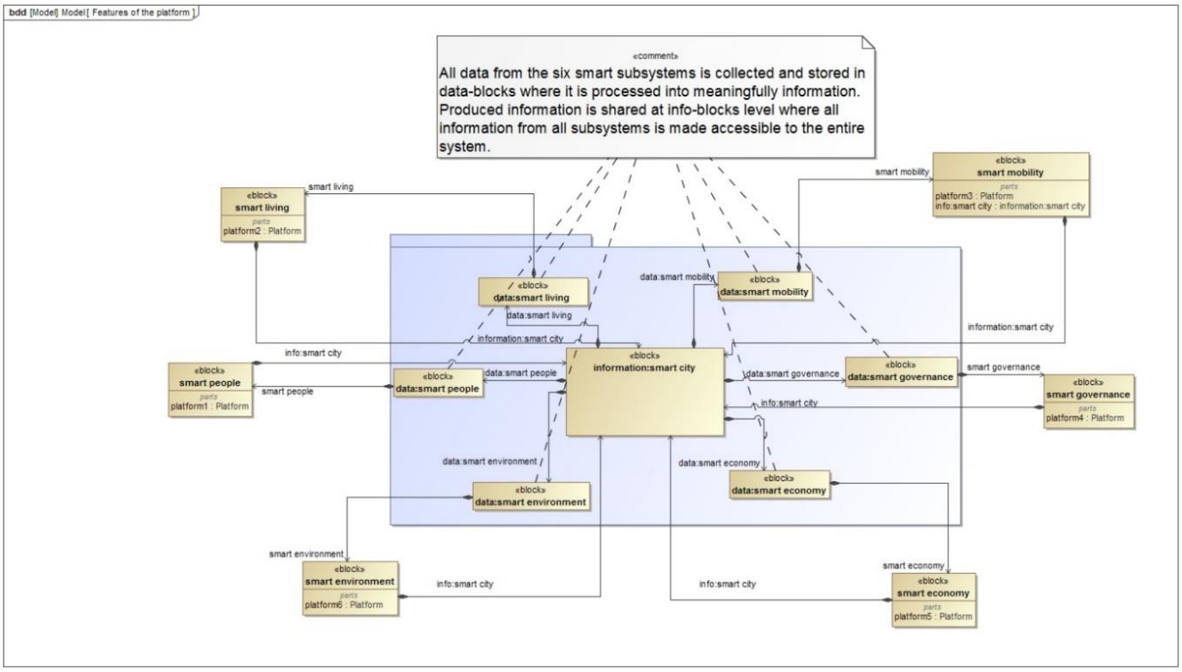

Figure 3. 8 The smart city platform operation structure.

To understand the operation of the presented model, a state machine diagram is presented on Figure 3.9. The diagram shows states through which the smart system of a city goes through in its operations as presented by the structure of the model on Figure 3.7. The sources of data will be the starting point through which data is produced by a number of means such as sensors, cloud-sourcing, etc. Data will then be sourced and stored at the level of data block which is presented as a data platform and it is at this level that data will be processed into meaningful information which will be stored by the information block presented as information platform. As it can be seen on Figure 3.8, every single smart subsystem sources its own data which it processes to produce information and transfers it to the information block. Data block and information block operate at the platform level as it can be seen on Figure 3.8.

Note that Figure 3.7 and 3.8 presents high level structures and a more detailed logical architecture later in Chapter Four, more specifically from Figure 4.5 to Figure going on to Figure 4.14.

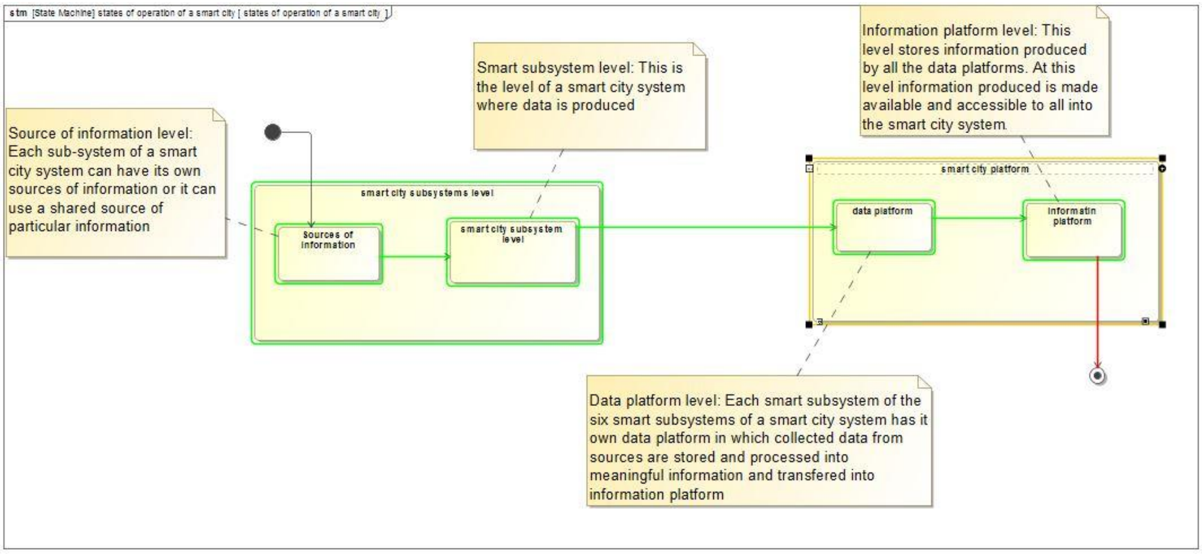

Figure 3. 9 High level illustration of operation of the model of a smart city system

3.7 Chapter summary

It was shown that the smart city concept is motivated by the necessity to cope with challenges faced by contemporary cities. The concept proposed a transition from a contemporary city system into smart city system. However, a city system is a large and multidisciplinary complex system and its transformation into smart city system was observed to be not an easy task. The fact that the city system involve multiple stakeholders and large information add extra constraints to its transformation process. Chapter Two of this thesis showed that, to cope with complexity, existing transformation approaches of city systems produced disconnected systems where subsystems were neither interconnected nor integrated. The normal logic of a system is that it is considered as a whole. This chapter described a system engineering approach, a potential way to deal with complex systems transformation, such as smart city systems, using MBSE methodologies and SysML while keeping them as a whole and well integrated. Connecting to one of the major objectives on this work, to develop a methodology to model of an integrated smart city system, this chapter exposed tools and methods, to be used later in Chapter 4, for development of the methodology development. This chapter described the SE approach, the MBSE methodology and the SysML in details, and later used the SE approach to presents an initial concept of an integrated smart city system.

The historic background to SE showed that it evolved as a solution to complexity of emerging systems. Over the last decades, SE has shown rapid advances due to increasing complexity, sophistication and diversification of systems in all aspects of life. Unlike other conventional engineering field, SE does not have fixed and predefined basic theorems related to science and physical properties but has been developed as set of methods to address complex and unstructured problems within particular contexts and circumstances. It is described as an interdisciplinary approach which is there to deal with complex problems of stakeholders and identify requirements which are used to design systems, to cope with complexity and test them to insure their success.

To assure consistency and traceability during the development process of systems, Pioneers in the field of SE such IBM, INCOSE and Vitech developed the MBSE methodologies. MBSE was described as a formalised and interdisciplinary approach to allow realisation of successful systems and associated methodologies were described. In the context of this research, MBSE supported integration of a smart city systems. More MBSA benefits were identified in this chapter and among them: leverage interconnection, better information management, solution to difficulties related to document-centric approach, etc.

Among various MBSE methodologies, INCONSE OOSEM eases systems integration and was selected for this work. It makes use of the model-based approach and integrates the OMG SysML, a modelling language developed by OMG, which is capable of using full potential of MBSE approach. SyML provide to users different types of diagrams which can be classified into two main groups in addition to requirement diagram: behavioural and structural diagrams. SysML was described in details in this chapter and it was shown that while SysML is a powerful modelling language which has a capability to model a wide range of systems, it also requires a robust tool to run analysis, check model consistency.

Among the SysML tools, the Enterprise edition of Cameo Systems Modeller was adopted for this research. It is a leading cross-platform collaborative MBSE environment which gives robust, smart and intuitive tools to verify requirement, track progress, define and visualise all systems' aspects. The cameo systems modeller was the tool to realise modelling of an integrated smart city system.

It was with the systems engineering approach that a conceptual model of an integrated smart city system was presented with a special focus on the information perspective. The structure of the proposed holistic model of a smart city system is illustrated on Figure 3.7. Every single smart subsystem sourced its own data from external sources (sensors, cloud sourcing, etc.) and processed it to produce information and transfers it to the information block. Data block and information block operate at the platform level as it can be seen on Figure 3.8. Initial operations of the presented model were present by a state machine diagram on Figure 3.9. The presented initial conceptual model was a starting point of a development of a method to model an integrated smart city system to be developed in details in the next chapter.

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CHAPTER 4

Modelling smart cities: A systems engineering approach

As it was shown in previous chapters of this thesis, the concept of smart city (SC) has been gaining popularity and cities have developed strong interest for transformation into SCs. However, given that a city is both a complex system of systems and a dynamic complex environment, achieving a state of SC can be challenging. Urban transformation into smart city has been straggling to produce an integrated city system due its complexity. This chapter presents a methodology helped by a Model-Based Systems Engineering (MBSE) approach and Systems Modelling Language (SysML) to develop a model of an integrated SC system. The model brings all subsystems to operate together in one system and focuses on the information perspective of a city system. Three scenarios are presented to illustrate how an integrated information platform can be a gateway and easy access to information in an SC system, as well as a starting point towards modelling an integrated SC system.

While Chapter Three focused mainly on describing the methods and tools of the new approach, Chapter Four completes the study objective of developing a new methodology to model an integrated system of smart cities and present a model of an integrated smart city system.

4.1 Introduction

Although globalisation has connected cities and improved collaboration among big cities, it also created competition among them. It is in the interest of every city to increase productivity and innovation with the aim of making itself desirable and attractive for living. While the observed urban population can come with benefits, such as increased labour market, it also comes with challenges, such as waste management, traffic congestion, pollution, surcharge of energy demand, etc. [15]. All this threatens sustainable urban development and creates a demand for efficient and innovative measures to deal with these challenges.

Technology has a major role in cities transformation and is a major SC enabler. The SC concept is by far built on information, with the main features being Information Technology (IT) and comprehensive application of information resources [213]. It can be deducted from [173] that an SC uses intelligent information systems to achieve a sustainable urban development, a definition that places information as a principle factor of the SC concept.

This concept has gained popularity and transformation of existing cities into SCs has been attracting significant attention from various stakeholders [15]. A city is a complex system of systems [214] and the rate at which cities are becoming complex was found to be faster than the rate at which theories were being developed to understand them [215]. To cope with cities' complexity, their systems have been divided into small individual systems that address issues thematically [29]. Although divisions of a city system into individual systems might bring solutions, it will definitely also make the city system even more complex. A SC system should achieve integration and efficiency [30]. To redesign cities into smarter cities means to transform them into more sustainable, integrated, and collaborative at all levels. A city can be considered smarter than another based on how efficient and integrated its subsystems are, as well as the degree of seamless flow of information among subsystems and the general public.

Many attempts have been made to redesign, model, and transform cities—the most complex man-made systems of systems [216] —into smarter systems. However, such transformation requires an appropriate approach to be achievable. A systematic survey by [15] showed that many projects with smart solutions have been initiated to address existing thematic challenges faced by cities, such as parking issues, air pollution, traffic congestion, waste management, etc. It is worth noting that it is still unclear how many projects and at what integration level projects could take a city to a fully SC system level. In this study, we propose a view of an integrated model of a smart city system. The aim of this chapter was to illustrate a methodology through which an integrated city system can be modelled efficiently by keeping all the main components together to allow the operation of an integrated system within the boundaries of a SC. The objectives were to present and test a number of scenarios to illustrate how the proposed system would react under a set of particular conditions.

To achieve the aim and objectives of this chapter, Section 4.2 describes and presents previous studies to benchmark the presented work in this chapter. Section 4.3 describes the proposed methodology and tools to model an integrated smart city system as well as the development process. Section 4.4 describes an integrated model of a smart city system and tested its behaviour. Section 4.5 presents the model operations and analysis. Section 4.6 gives the conclusion of the chapter.

4.2 Background: Smart City System Model—A Systems Approach

While some researchers are still trying to better understand how a city system can be redesigned [23], there is still no clear methodology that allows integration of all subsystems of an SC system. Many conceptual models have been proposed to accomplish such a task. In [217] it was argued that proposed approaches in the literature were often not complete, not integrated, and non-communicating. They pointed out the absence of uniformity of the SC concept development, definition, and the lack of a methodology to evaluate developed models. They proposed a methodology for planning an SC through a model based on matrices; In, [216] they focused on the interaction between a city and products services to propose a 'product-service system engineering approach' based on systematic engineering and sought to integrate the city service systems and product service systems. In [214] the authors built Information Technology (IT) to present a model made of a set of layers represented in a Geographic Information System two dimensional space. [93] looked at an SC system as composed of six layers which are green, interconnected, instrumented, integrated, intelligent, innovative, and presented a model which addresses global sustainability challenges in a local context. [218], motivated by the need to integrate a city system and human factor, presented a user-centred approach to design and model SCs building on application of systems engineering. [23] stressed the need for integration as a systematic answer to urban challenges, a need for tools to understand the complexity of the SC concept, and its capacity to solve urban challenges. In a case study on Vienna, the authors proposed an integrated conceptual model to respond systematically to urban challenges. In their study, they argued that an SC is an integrated and multi-dimensional system aiming to address challenges faced by cities and proposed a model that follows an approach linked to three main issues: the role of government and stakeholders, the role of displaying a comprehensive vision towards SCs, and SCs as a tool to tackle urban challenges. [219] worked towards the development of a platform infrastructure for a sustainable smart mobility subsystem. Their study proposed an information infrastructure architecture development method which presented a cycle from the development phase to the operation phase. The proposed platform focused on mobility information infrastructure and consisted of three components: the information collection component, the platform component, and the information provision service component.

The above previous study shows that although the necessity of integration of all six identified components of an SC system in [220] is evident, it is still yet to be achieved. The presented previous work displayed the willingness to integrate SCs systems and make them work together as a unified whole and share information seamlessly. [172] observed contrasting views and the lack of an integrating view in an existing smart city system. It was observed that a smart city was a system that performs well in all smart subsystems which operate as interrelated entities and form a unified whole. [220] also showed that each subsystem of a city system had its own audience and services with a specific targeted subsystems to be transformed among the identified subsystems of a smart city system in [14]. Therefore, there was a disconnection of subsystems of a smart city systems and the need for system integration. Information and communication technology is at the forefront of a successful SC system [173] and there is a necessity of a well-integrated SC system—a set of elements/subsystems which interact with one another and which are viewed as a whole entity/system [169]. It is evident that there is a need to develop an efficient methodology which would allow the construction of a model of a fully integrated SC system that would allow all smart subsystems to share information.

4.3 Methods and tools

Given that not all complex systems are software systems, complex systems such as cities require methods and tools to be modelled, analysed and integrated. Model-Based Systems Engineering (MBSE) is a potential and robust methodology to model an SC system and is itself a contribution, and SysML, as tool, facilitates MBSE to add automation and enables analysis of a built system. MBSE could be a most viable option when it comes to SC system modelling and allowing information and technical communication across smart subsystems. MBSE can improve understanding of a system's needs and constraints, can ease the analysis while allowing to a bigger picture view when making big decisions and generating a whole system which is coherent and not dominated by a single perspective of a particular subsystem [221]. It extends beyond the engineering domains to support complex modelling and the integration of systems. In this study, MBSE was complemented by SysML, a tool capable of modelling a wide range of systems [222] developed by the Object Management Group [223]. It supports the practices of MBSE to develop solutions to complex and challenging problems such as analysis and multiple views visualisation of complex systems [169]. SysML itself is a standardised language and its advantages are that it is unambiguous, enforces consistency, prevents attempts at making incompatible connections, improves precision and efficient communication, is scalable, manages better complexity, and detect errors on any omissions in the early stage of systems development. [169] presented the taxonomy diagram which established the intended linkage between SysML taxonomy diagrams.

Like all other tools, SysML has limitations. It lacks the potential to independently execute mathematical expressions which are complex. In such a situation, co-simulation with other analysis tools such as MATLAB or any other compatible tool might be handy.

Model infrastructure is an important element to achieve the objective of system modelling work. Cameo Systems Modeller is a cross-platform collaborative MBSE by MagicDraw which provides a robust smart tool to define, visualise and track systems aspects and design processes [221]. This tool facilitates the visualisation of all aspects of systems in a standard way and complies with SysML diagrams. Diagrams included in SysML allow specification of system's structure and behaviour [206].

In this chapter, we develop an MBSE methodology to analyse a SC system and cope with its complexity through operational simulation. It focused on the conceptual design phase of a SC system and a model simulation was conducted to test it.

In general, system analysis can be carried out through simulation of models with or without a detailed system architecture. This study demonstrates that MBSE methodology and SysML can support SC system integration and analysis. To understand the system's operational side, emphasis was placed on system structure and logical architecture and focused on proper linkage between all subsystems of a city system and the system was executed under certain operational circumstances for analysis.

4.3.1 System model development process

Figure 4.1 presents processes of the system model development. It displays the level of detail expected in the system, the system content and the outcomes which eases communication among all SC subsystems. It includes the six components (subsystems) [15] of a city system, an information platform (Figures 4.2 and 4.3), and users' benefits for easy information access from the information platform. The need for such integrated platform is driven by numerous factors, such as:

- Better monitoring of the city;
- Gathering information from all sources for easy and fast access to information and fast reaction to incidents or any emergencies;
- Dynamically acting on urban population needs; and
- Having reliable information and services to the public for better decision making and efficient use of resources

Before information can reach the platform, data is collected from different sources and processed into meaningful information. However, this process was out of scope of this study and the focus was on information integration, the structure of the information platform and the behaviour of the model when subjected to certain scenarios.

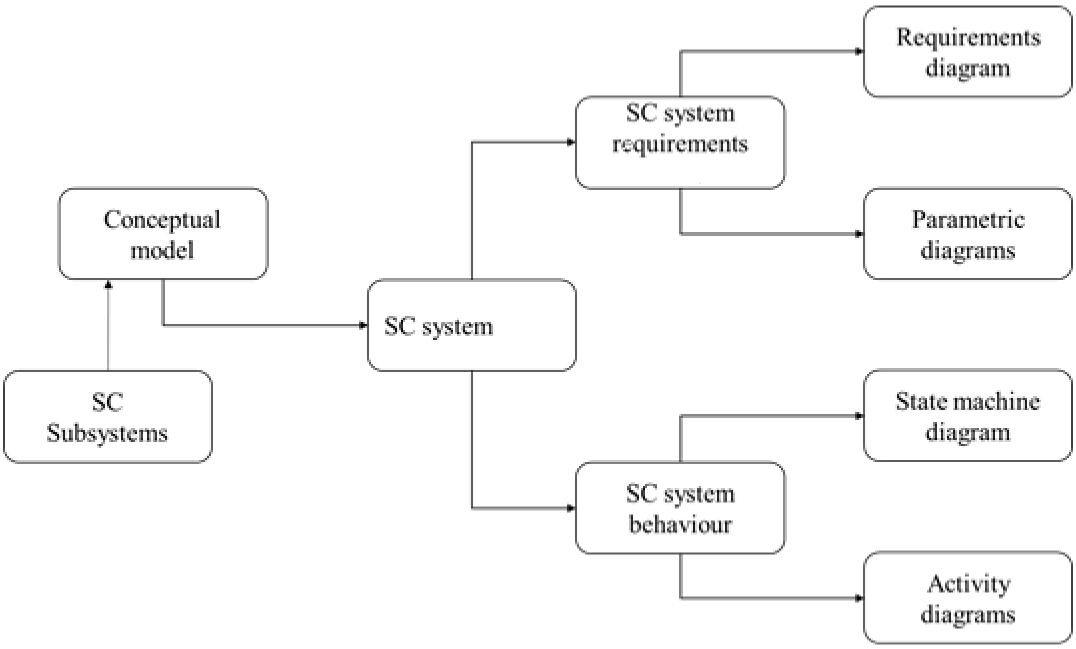


Figure 4. 1 Model development process.

4.4 Components and logical architecture of a smart city system model

In this section, an MBSE methodology to design and model a SC system with an integrated information platform is presented. Six components of a smart city systems were identified for the first time in [220] and were adopted by many researchers later [15]. As illustrated in Figure

4.2, the six identified component constitutes the subsystems of a smart city system. The structure of the conceptual model is illustrated in Figure 4.3.

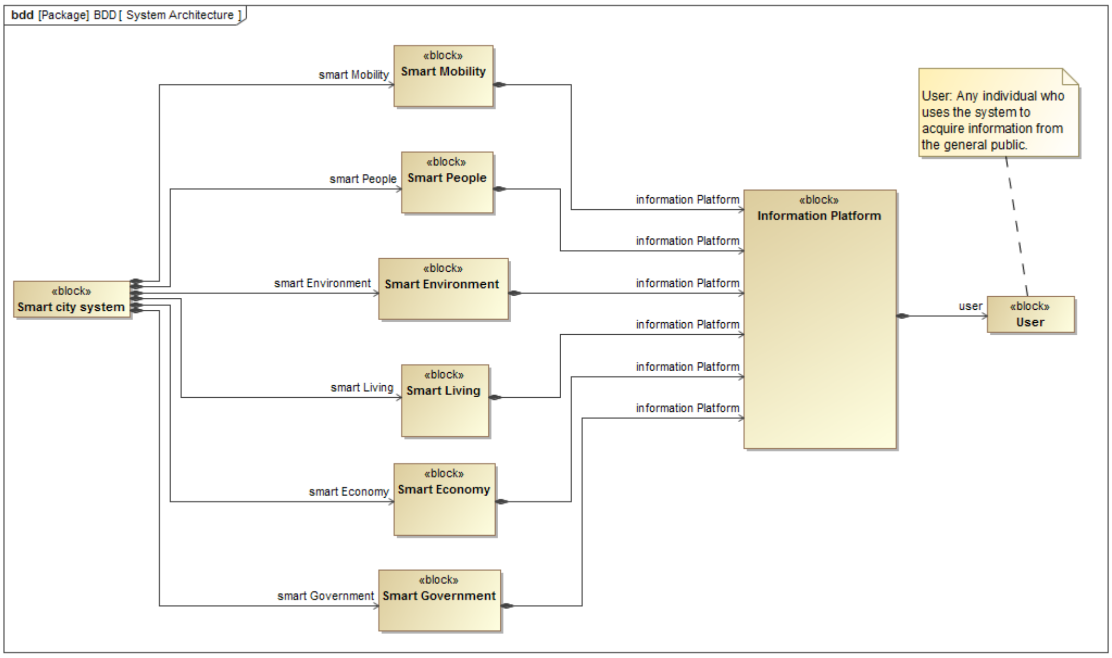


Figure 4. 2 Smart city **(**SC) system model—logical architecture.

The architecture of an SC system is defined in a SysML block definition diagram (BDD) (Figure 4.2). An important aspect of this model is the inclusion of an integrated information platform which is a gateway to easy information access within a smart city and allows interaction between all the smart subsystems of an SC system.

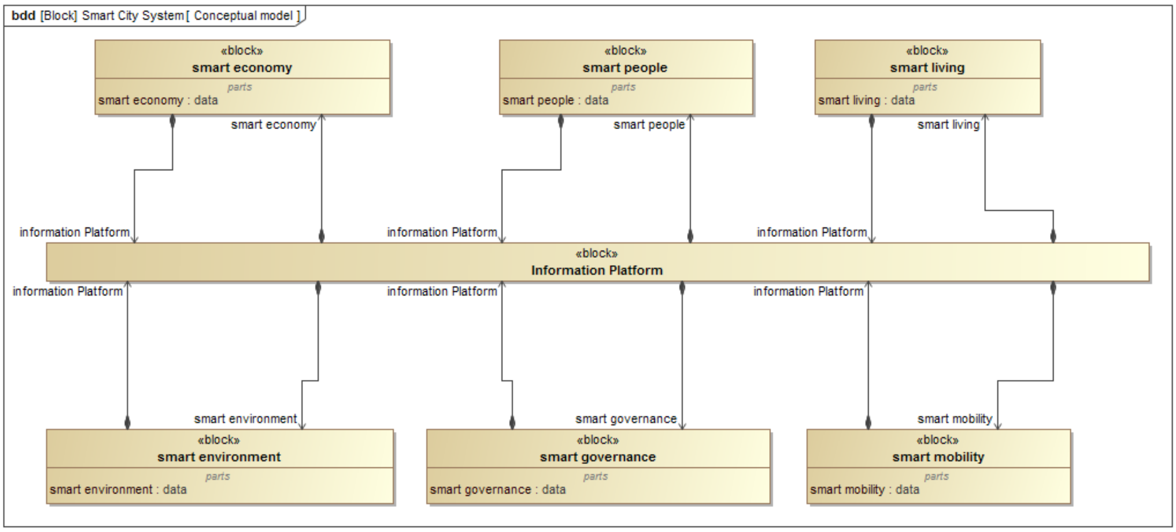


Figure 4. 3 SC System model—conceptual structure— Adapted: [26]

In the context of this study, the data was generated and processed into meaningful information at the level of each smart subsystem, as illustrated in Figure 4.3. The resulting information was then stored at the level of an information platform where it can be accessed. The information platform of an SC system is designed to focus on information sharing between the six smart subsystems of an SC as a method for an information integration process.

4.5 Model operations and analysis

Often, in SysML modelling projects, there is a certain order which is followed for different diagram construction. The general order begins with the identification of system requirements which are illustrated in Figure 4.4 by a requirements diagram from which an activity or a state machine diagram was created to introduce the systems' behaviour and satisfy the requirements. Block definition diagrams were then created based on information in activity diagrams. From block definition diagram, parametric diagrams can then be generated. Figure 4.4 shows the requirements diagram of an SC system in which the main task of the system is described by the main requirement which is to develop a scalable SC information system which will integrate information from all levels of a SC system and make it easily accessible on the information platform.

Figure 4.4 presents the initial development of the requirements. It shows each requirement with an identifier ("id") and a descriptive text ("txt") to facilitate traceability. The diagram is decomposed into a set of sub-requirements which illustrate other relationships, such as refine, satisfy, and derive to support traceability. Identification of requirement is a fundamental part and critical factor to the success of system development [206]. There are various possibilities of classification of requirements, such as user requirement and system requirements. The requirement diagram belongs to SysML behavioural diagrams and its main purpose is to register all the relevant requirements of the system, to capture the hierarchies of requirement and relationships such as derivation, verification, satisfaction and refinement. The requirement diagram shown in Figure 4.4 illustrates the conditions to be satisfied and functions to be performed and achieved by a SC system. The diagram represents a hierarchy of requirements and depicts the requirements captured in a text specification and their inter-relationship. The diagram contains requirements for functional objectives, security objectives, interface objectives, and usability objectives.

Although the diagram in Figure 4.4 presents the SysML requirement diagram, not all aspects of an SC system operations are captured, but it does demonstrate common model operations and can be supplemented by an increase of details.

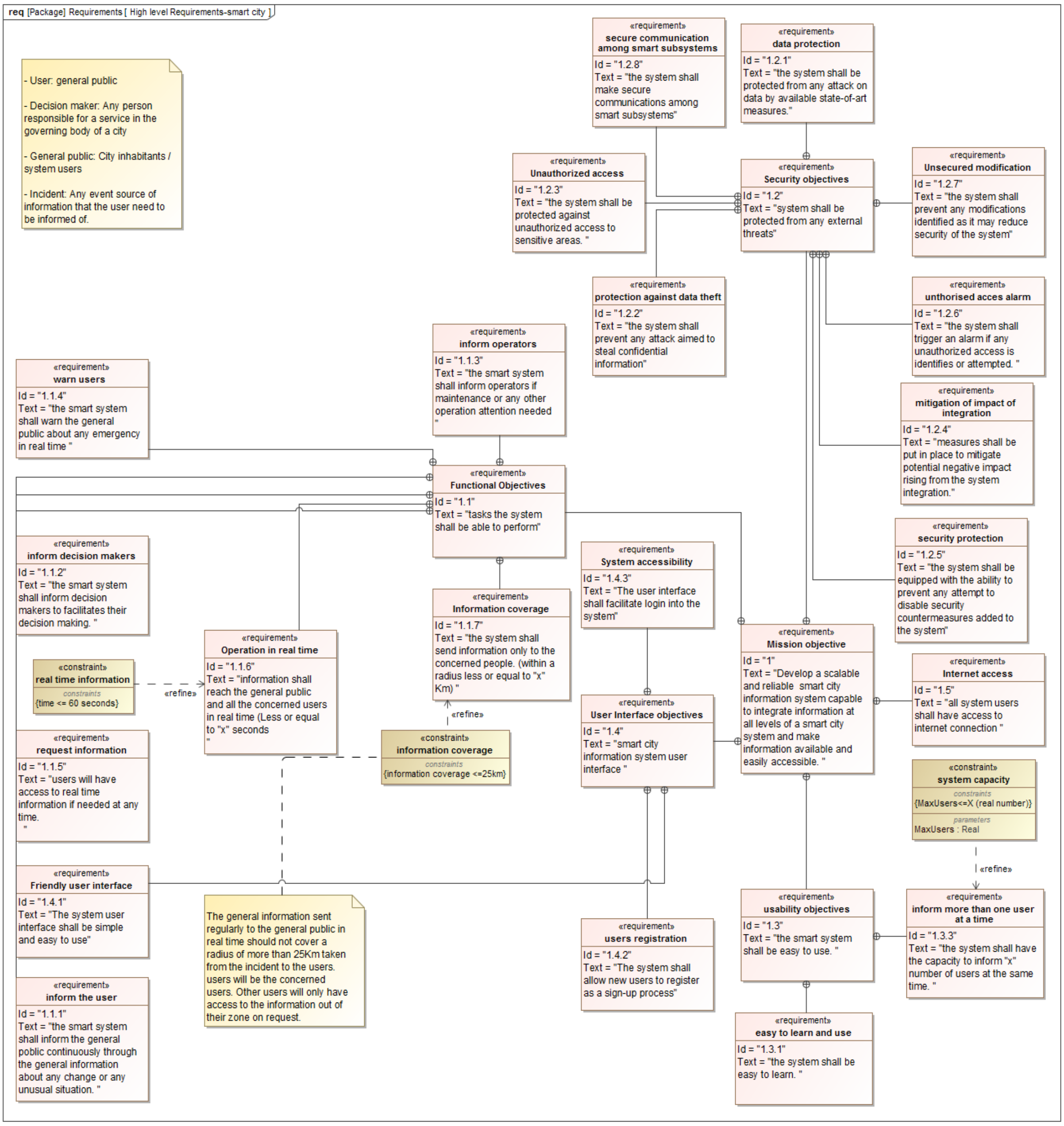


Figure 4. 4. Initial SC system requirements development.

To understand how the system behaves, as presented in Figure 4.4, the state machine diagram illustrated in Figure 4.5 specifies the system states which are presented into a sequence of events which a system goes undergoes throughout its lifetime to respond to an event without deviating from the requirements needs.

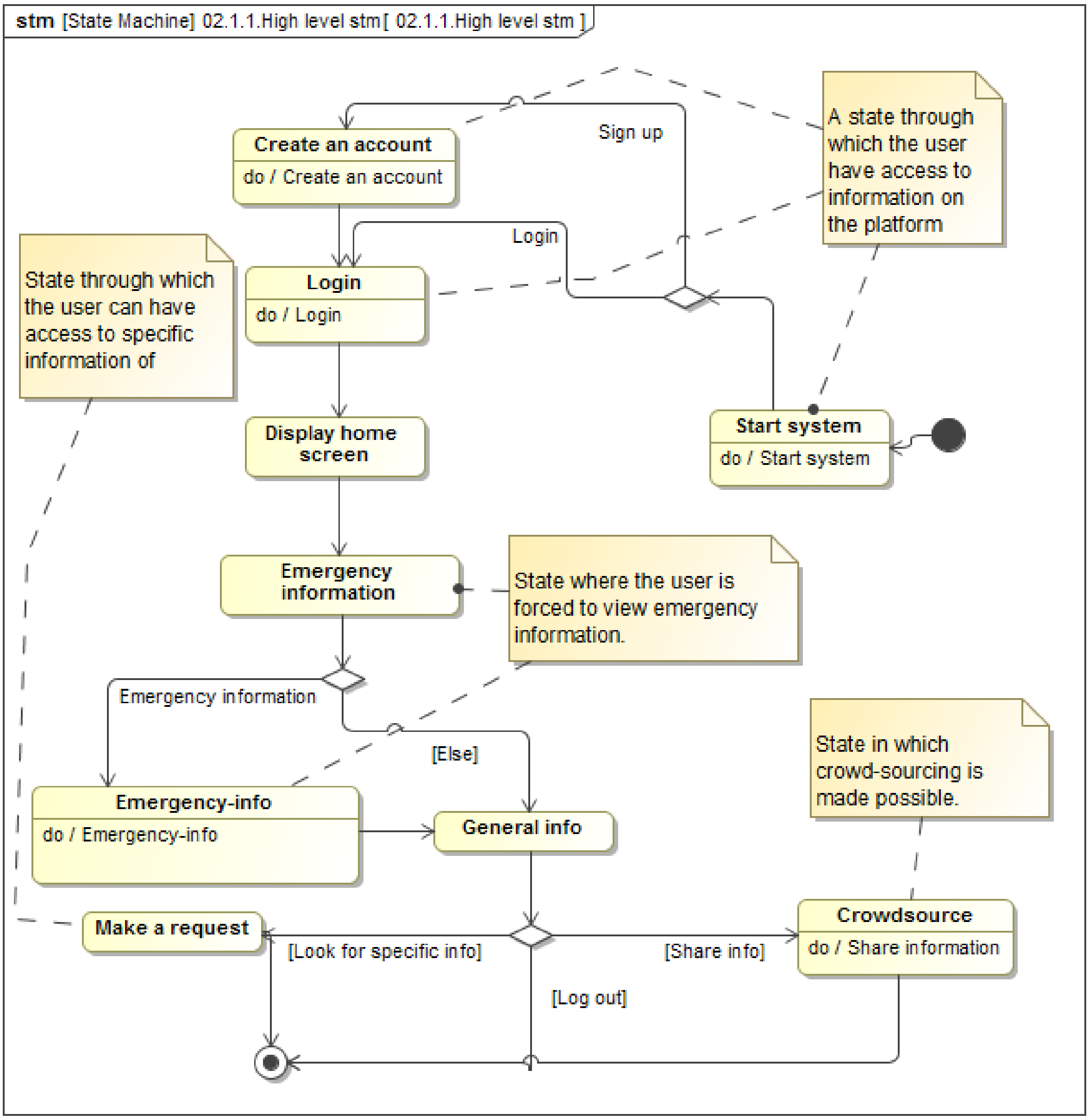


Figure 4. 5 High-level behavioural state machine diagram for the information platform.

The triggers cause transition, which can be a signal, a change of condition, etc. A condition, "Guard", must be true for a trigger to initiate a transition and will act on a state and result in a change of state [169]. Figure 4.5 illustrates a state machine diagram which focuses on the information platform and defines how the system's states change as transitions are triggered. The diagram represents the behaviour of the system in terms of its transition between states which are triggered by events. For example, in Figure 4.5, the system cannot respond to event 'login' before 'sign up'. The figure illustrates the user's perspective and how the information platform behaves within the states it goes through once subjected to users' activities. It presents a high-level diagram where the top functions focus more on security, awareness of emergency situations, general information and crowdsourcing, which are normally in line with the requirement and the purpose of system development. Note that 'users' stands for the general public looking for quick response information.

The default state of the system is the 'start' state, illustrated by Figure 4.6. This is the first action of the system in which the input is the user's details, which may require simple input of user identifiers if the user is pre-registered (Figure 4.7), or the whole process of registration illustrated in Figure 4.8, which would be the user's personal details, if they are a first time user.

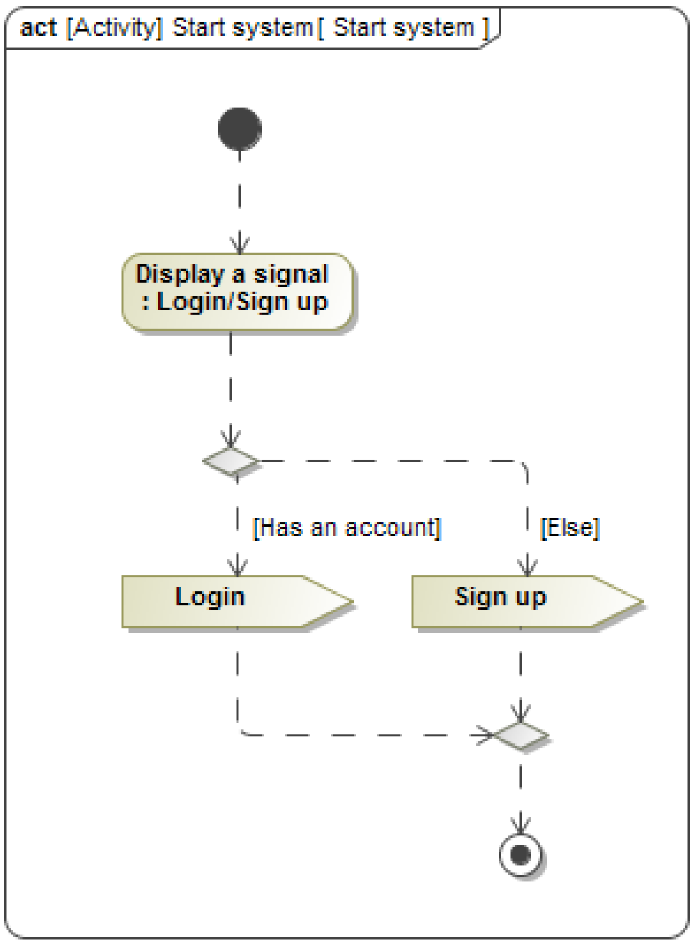


Figure 4. 6 Activities performed in 'start system' state of the SC system.

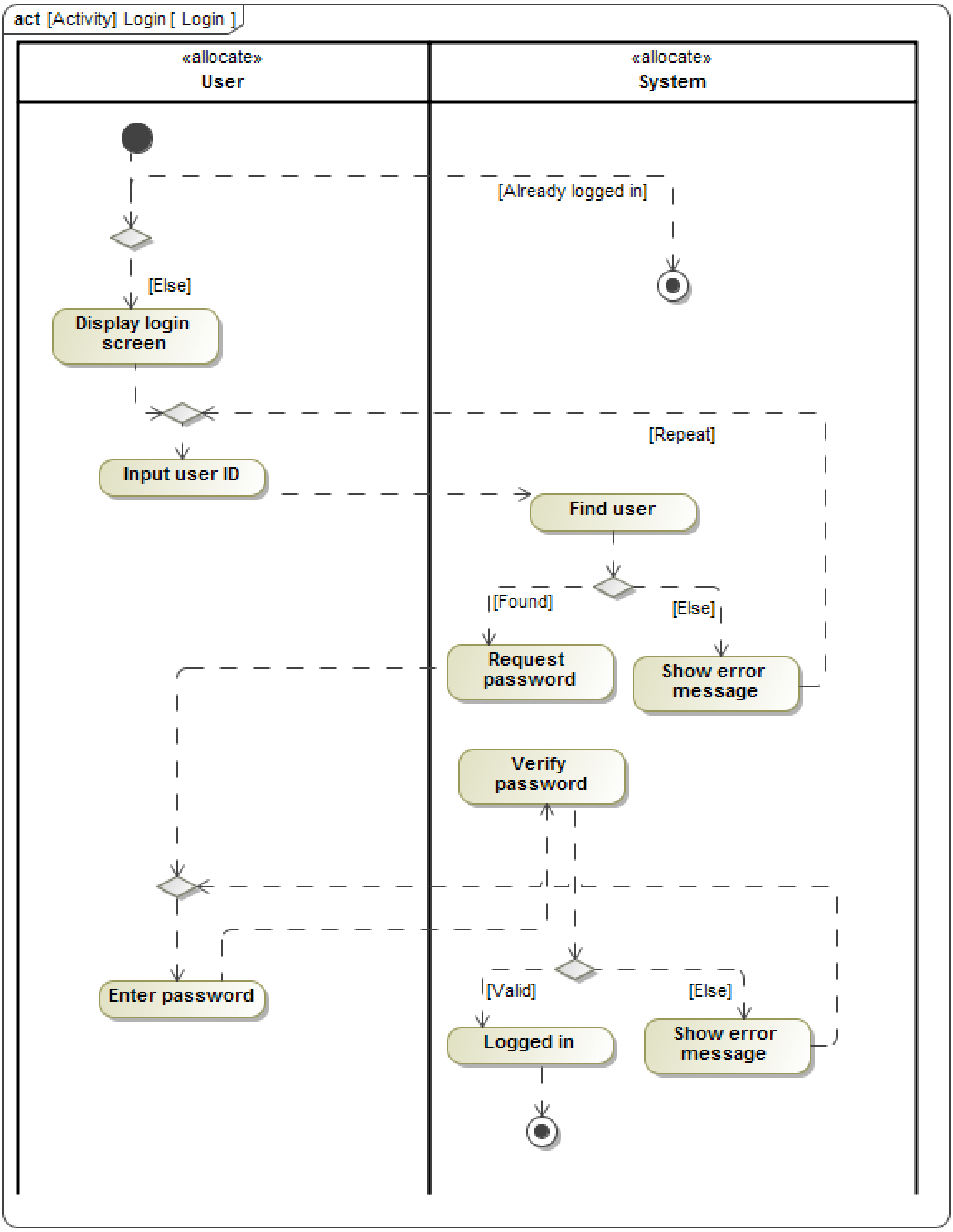


Figure 4. 7 Activities performed in the 'Login' state of the SC system.

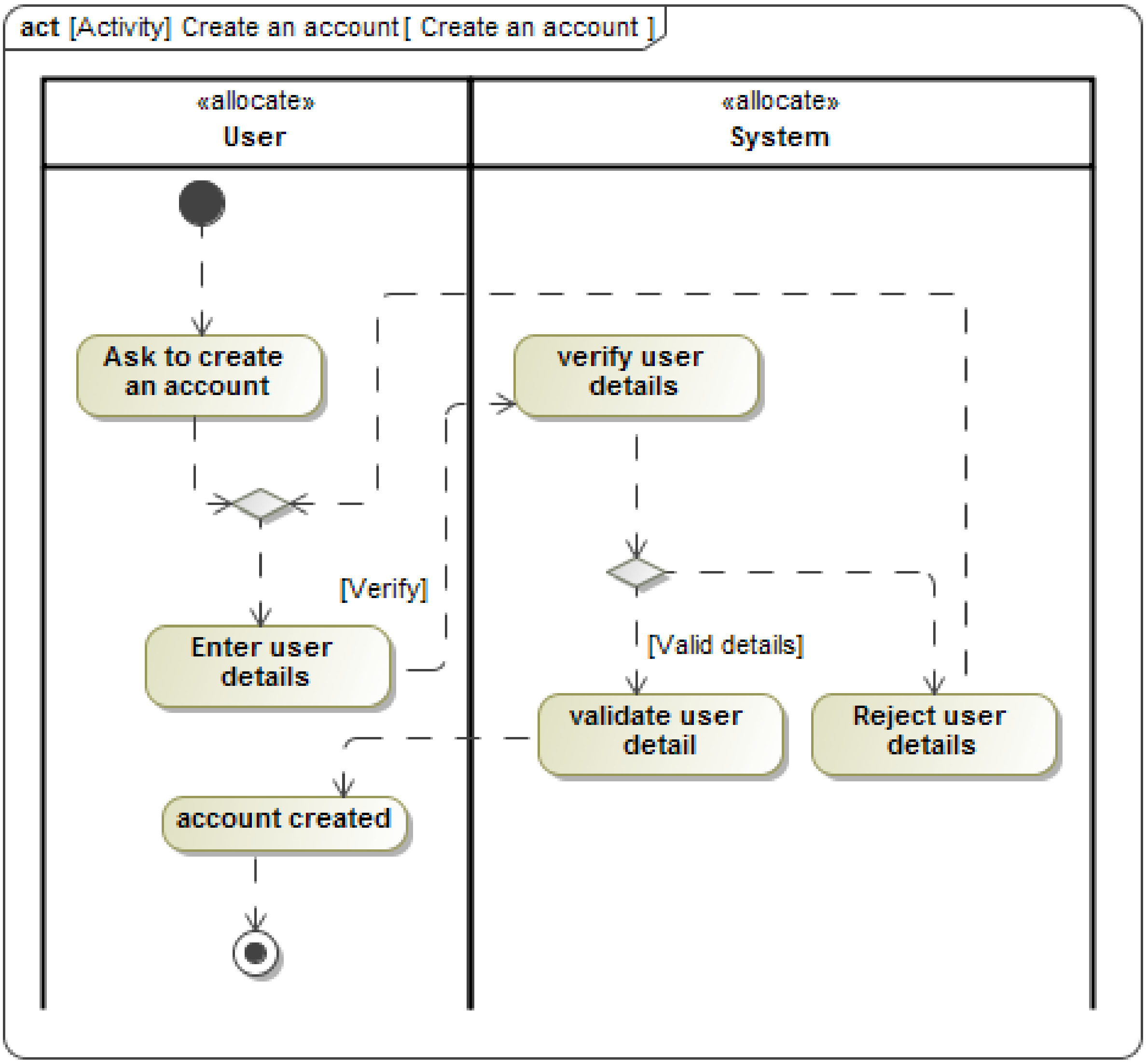


Figure 4. 8 Activities performed in the ‘create account’ state of the SC system

Once the user has been granted access to the information platform, as part of the transition to the next state, the system presents automatically relevant emergency information to the user shown in Figure 4.9, which is information the user need to know, such as, in the case of mobility, traffic congestion building up due to an accident on the current user’s route. The next state presents general information. At this level of the system, the user has three choices which can change the state of the system from general information to share information (Figure 4.10) if the user wishes to share information as part of the crowdsourcing action put in place in the system, or from the general state, in which information judged relevant to user, depending on their location, is presented, or advanced search of information, if the user is looking for particular information not found in general information, or the logged-out state, if the user wishes to exit the platform.

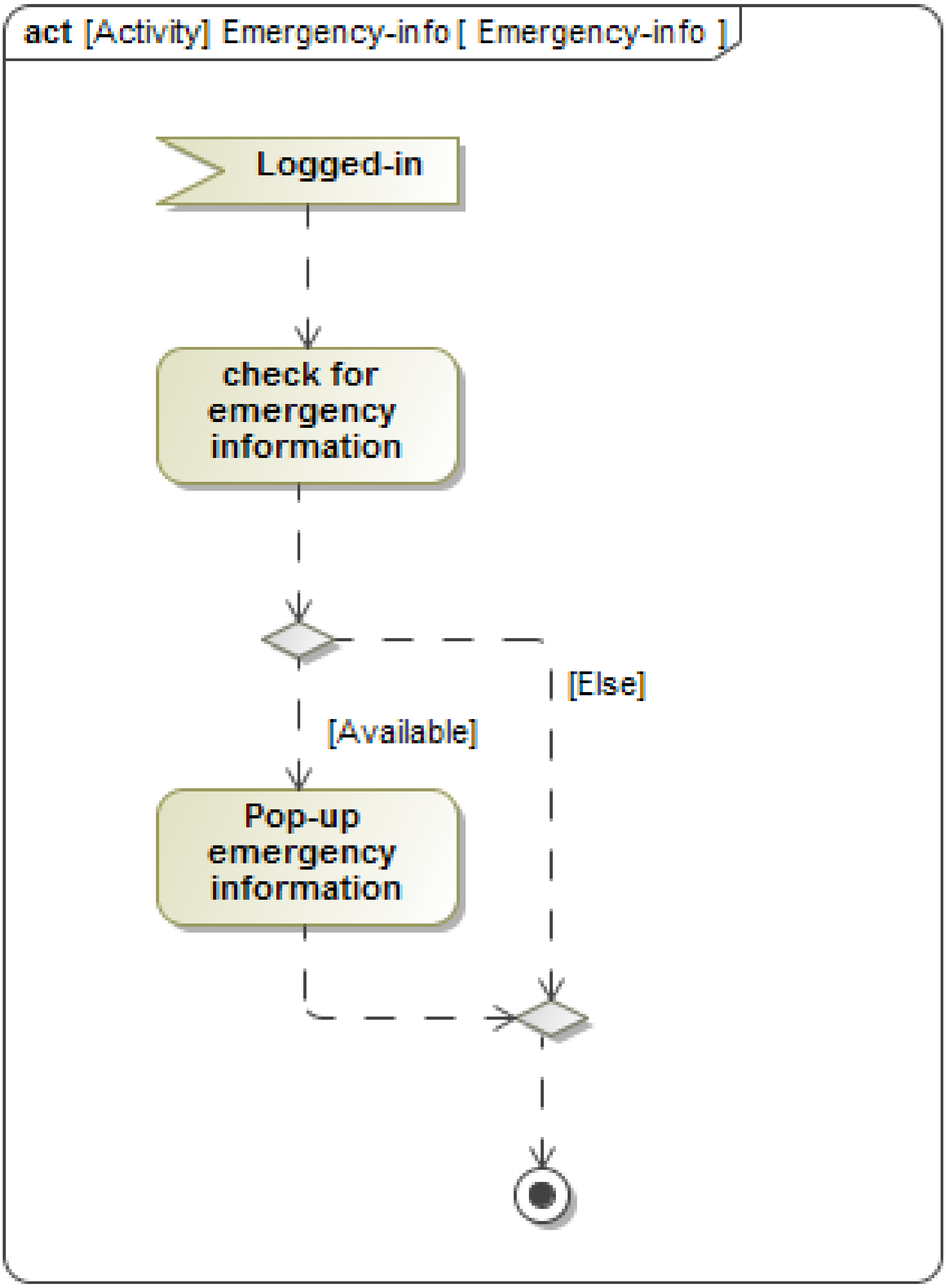


Figure 4. 9 Activities performed in the 'Emergency-info' state of the SC system

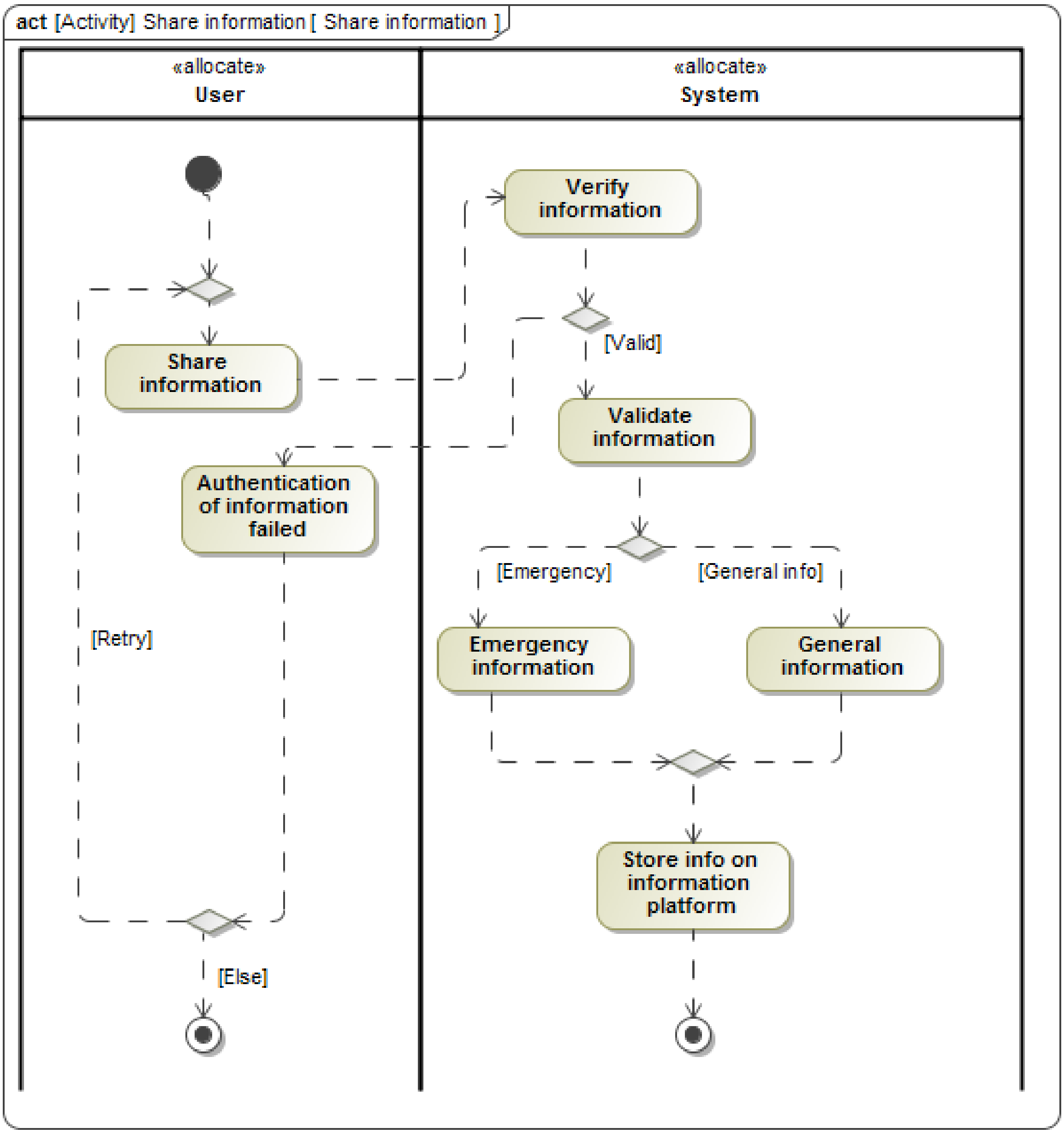


Figure 4. 10 Activities performed in the 'share info' state of the SC system

The presented state machine diagram specifies the life cycle of the system in terms of states and transitions and used activity diagrams to illustrate the behaviour as specification of how the system responds to stimulus.

The presented activity diagrams are integrated in the composition system behaviour, which is captured in the state machine diagram presented in Figure 4.5. The activity diagram describes what the system must do to satisfy identified functions, shows the input actions of the users and the reaction of the system to the user inputs. When an activity is initiated, the execution starts at the initial node, and it then is initiated to the next activity until it reaches the final activity, and later, the final node. For the system (Figure 4.5), a set of actions are performed within each state as activities, which are executed in activity diagrams before the system can change to the next state. The presented activity diagrams include the semantics for precisely specifying the sequence of actions and a control flow represented by a dashed arrowhead line specifying the sequence of actions. Activity diagrams illustrate that the dynamic aspect of the system and are constructed in a manner that allows the execution of system through an engineering technique of forward and reverse. However, among their limitations, they do not have the capability to show the flow of messages among activities and do not give details of behaviour of collaboration among objects. Therefore, the activity diagram cannot replace the state machine diagram. The control flow provides constraints on when and in which order the action within an activity is executed and it does not start until the source action is completed.

The constraints are presented in blocks (Figure 11) as refinement actions of the system requirements diagram (Figure 4.4). Constraint blocks are special types of blocks with which equations can be defined and they have two main parts: parameters and expressions that constrain the parameters. This allows the support of parametric model construction [169], which can be represented using parametric diagrams. In general, system design requires engineering analyses to be performed. Such analyses may include reliability of performance of the system under certain scenarios. Parametric diagrams make it possible to capture constrains and create systems of equations to constrain properties of a block or particular requirements.

The functionalities of a system are mainly based on scenarios [206]. To analyse the behaviour of the presented model of an SC system, three scenarios are shown in parametric diagrams. The scenarios test the behaviour of the system when subject to capacity constraint, information delivery as time constraint and a constraint of defining the target of particular information. Figure 4.11 (a, b, c) illustrates the constraints imposed on the system to test its functionalities. The presented constraints were adopted with the particular objective of analysing the system reaction when subjected to those three conditions.

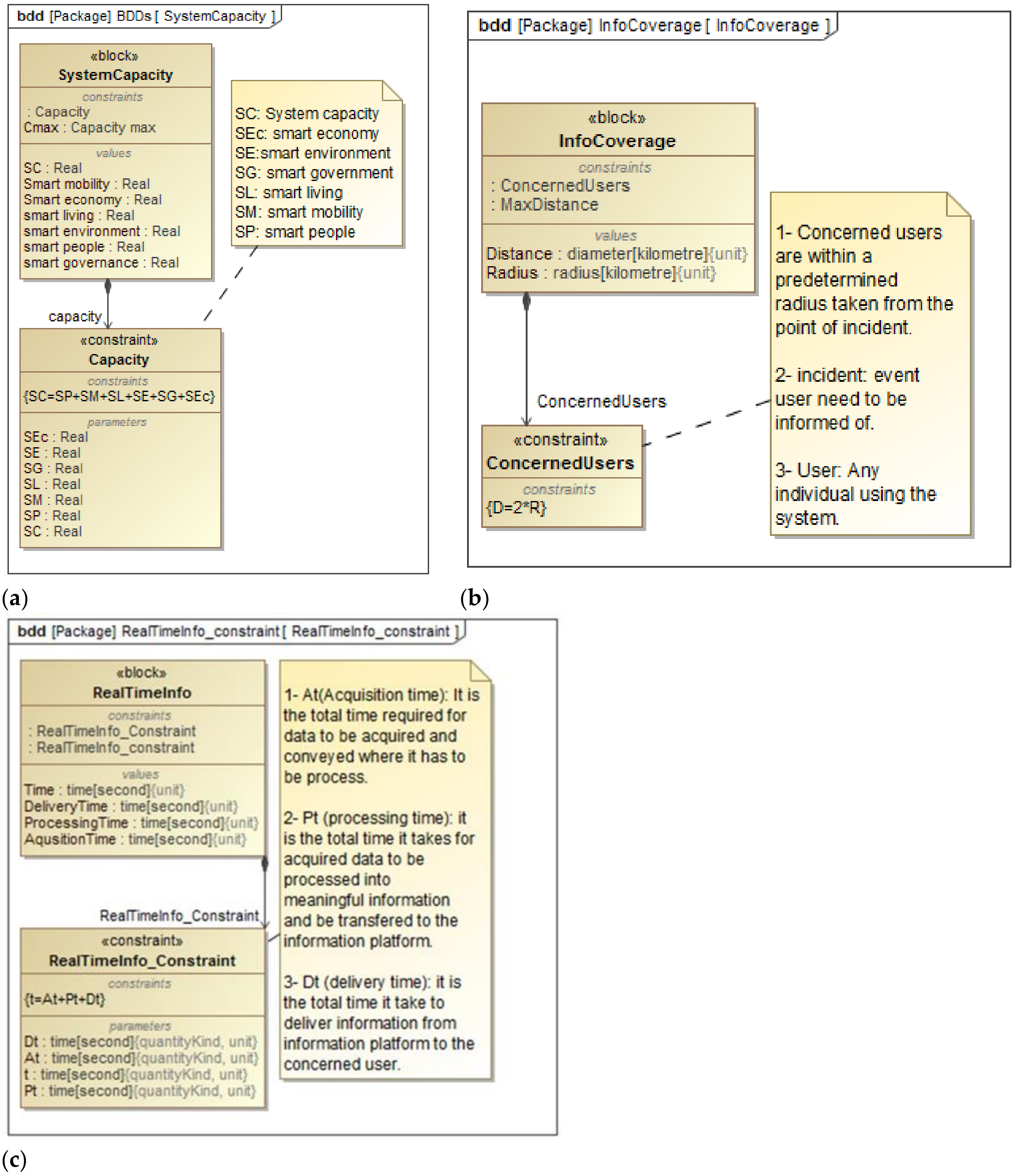
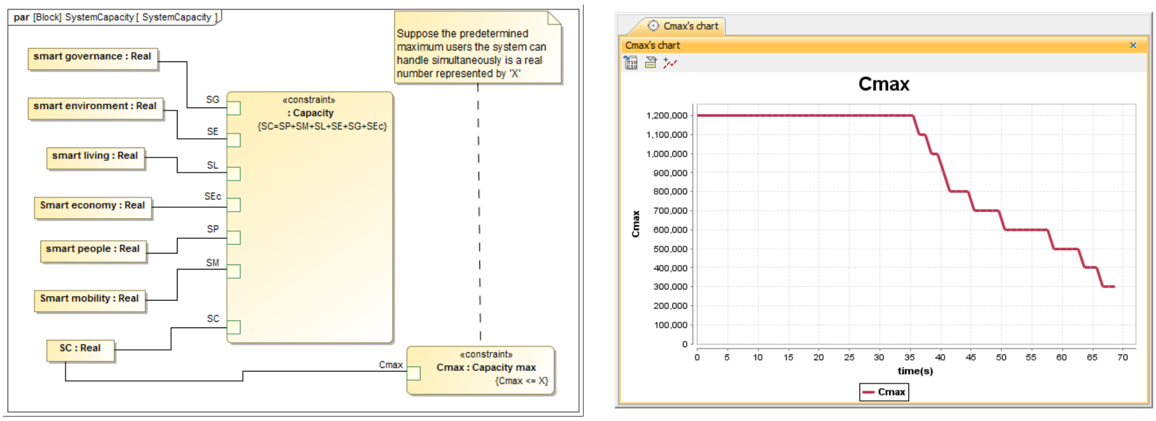


Figure 4. 11. (a, b, c) Constraint block that defines parameters of equations for analysis

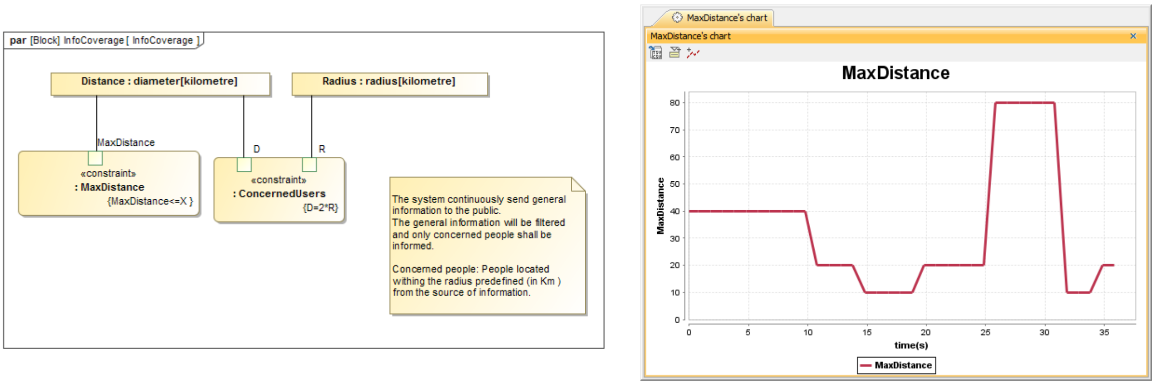
Figures 4.12, 4.13 and 4.14 show parametric diagrams for the constraint blocks presented in Figure 4.11 (a, b, c). Given that constraint blocks do not show all the information that interconnects constraint properties, specifically, relationships between properties and parameters, this information is expressed by parametric diagrams through the connectors in Figures 4.12, 4.13, and 4.14.



(**a**) (**b**)

Figure 4. 12. (a) Analysis of the capacity of the system (b) time series chart

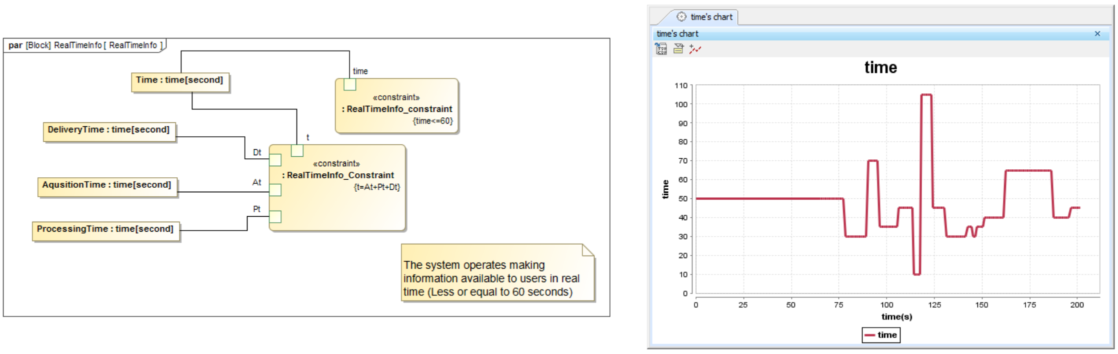
Figure 12(a) shows that the information stored on the information platform comes from different sources and locations and only the concerned users, identified based on the distance between their location and the location of the incident, are to be informed of a particular incident if needed. This scenario tests the system by setting the concerned users at a particular distance from the source of information, which is, at the same time, the location of the concerned incident. Figure 12(b) is a time series chart which illustrates a continuous process of identification of concerned users to inform them.



(**a**) (**b**)

Figure 4. 13. (a) Information coverage (b) Time series chart

The third scenario is illustrated in Figure 14(a) and tests the delivery of information in real time. The scenario set time to be considered as real time 't' (in seconds) which is the time required for the SC system to acquire data from an external source, to process it into meaningful information that can be understood by the users, and to transfer it to the users. Similarly to the previous scenarios, this process is continuous in time, as it is shown on the time series chart presented in Figure14 (b). The scenario presented three parameters representing the time required to acquire data (t_A), the time required to process data into meaningful information (t_P), and the time required to deliver information to concerned users (t_D).



(**a**) (**b**)

Figure 4. 14. (a) Real-time information (b) Time series chart.

4.6 Chapter summary

This chapter targets the information perspective of a smart city to highlight how an integrated model of a smart city system can be developed using MBSE methodology. A review of prior research revealed that the purpose of the process of transformation of contemporary cities into SC was to deal with the present challenges faced by the city and to counter future challenges. Multitudes of approaches and initiative aiming to model and transform contemporary cities into SCs have shown contrasting views and lacked an integrative view. Modelling complex systems such as the SC system can be challenging, but with the MBSE method powered by the SysML, a graphical modelling language can help with such a task.

Recalling that this chapter was motivated by the necessity to produce a methodology to model an integrated SC system, the results presented herein initiated procedures that began with an initial high-level requirement diagram of a smart city system and those requirements were used to initiate the external design of an experimental model simulation for system analysis. The presented model of a smart city system strengthens linkage in the architecture of a SC system development and system analysis. Procedures that use SyML products to support MBSE methodology and development of external structure of a smart city system model and simulation for analysis were described. This chapter demonstrated how this methodology is a best fit for systematic city transformation and integration of information for easy access and effective operation. Using MBSE, SysML, and a Cameo Systems Modeller, the presented methodology sets the stage for how to model a system of a SC and address the necessity to have all its subsystems interrelated, connected and integrated. The analysis performed on the model through scenarios was for testing purposes to understand the behaviour of the proposed model, interaction of elements, and verification of how the system responds when subjected to particular events. The presented integrated model allowed us to gather information from all the smart subsystems of an SC system on an information platform which supports multiple use cases. While current practices of transforming city systems into smart city systems show a disconnection and lack of unification as a whole, the transformation approach presented is suitable for this study because it emphasizes and presents an integrated system as opposed to existing approaches. Given that the defined and described methodology links the SC system architecture and analysis, the proposed system model can be a starting point for cities to develop their own integrated model and platform in their specific context.

To deepen the understanding of how information flow throughout the presented model of an integrated smart city system, the next chapter, Chapter Five, gives an even better visual of how more complete information, obtained through an integrated system, is beneficial as it is one of the many advantages of an integrated smart city.

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CHAPTER 5

An integration perspective of a smart city system

This chapter tests and validates the presented novel method of smart city system integration. This is achieved through a case study and the results showed that in a smart environment where ecosystem services are valorised, and in a smart city system where subsystems are integrated, air pollution emitted by vehicles (in smart mobility) can be removed by taking into consideration information related to air pollution reduction (in smart environment). The case study is presented to demonstrate that, with an integrated smart city system, information outputs on travel decisions were different and more valuable. The case study explores the operability of the system, its limitations, and potential future improvements.

5.1 Introduction

Observed rapid urbanisation and projected increases in urban populations in cities around the world motivate city planners and policy makers to consider how to sustainably manage resources in an environment that meets urban population needs. Based on [224], 54% of the global population lives in urban areas. In Europe, up to 75% of the continent's population live in urban areas, and these numbers are expected to reach 80% by the end of 2020 [1]. We have entered an urban era where cities around the globe are being challenged by rapid urbanisation and there has been an increasing awareness of problems related to the environment and sustainable urban development.

Fuelled by the development of technology, the concept of a ‘‘smart city’’ has taken over as a solution to challenges faced by cities. Although this concept is still criticised as too techno-centric [225] and lacks proper conceptualisation [10], its popularity has not stopped growing with combined objectives of enhancing the quality of life, Information and Communications Technology (ICT) development in urban areas, adopting new ways of governance, and concentration on sustainable development and human capital [10]. A smart city concept comes together with more analogous terms, such as virtual city, intelligent city, ubiquitous city, knowledge city, etc.—all of which were blamed for lacking a ‘‘people’’ component [1]. The smart city system also has many definitions [1,10] and appears not to have a one-size-fits-all definition. This highlights its complexity as a system with six subsystems. Dirks & Keeling

[133] stressed the need for an integrated city's subsystems in creating a smart city, and the idea was supported by Moss Kanter & Litow [134], who argued that a smart city will not be created by infusing technology in subsystems one by one but that the city should be treated as a whole entity. Some work separated the concept into numerous features with the complexity to manage a city in a holistic way [29,167]. From a technology perspective, the smart city concept is mostly built on ICT, and the concept is seen like a good strategy to achieve urban sustainable development, to meet the need of citizens, and to preserve the environment [226].

The application of the smart city concept is still fragmented and requires integration of all subsystems [1,14,23,133,134]. Some authors [172] observed a lack of an integrating view with regards to transforming contemporary cities into smart cities. They also noticed that the way the smart city concept is approached presents disconnection of the subsystems. In an effort to develop a method for an integrated smart city system, some researchers [23] focused on an information perspective of the smart city concept (see Figure 5.1).

This work builds on an integrative line of inquiry to propose a scenario that highlights and tests a new approach of information integration in a smart city. The core objective of this chapter is to provide a viable solution to the prevailing integration issue observed in the process of transformation of contemporary city systems into smart city systems. Through a case study, this work introduces a novel vehicle smart routing system to highlight the integration approach, an approach that maximises the benefits of completeness of information. The chapter stresses the benefit of an integrated smart city system and presents a novel approach to how such an integrated system would function subject to a particular scenario. The focus is directed to smart mobility and smart environment, two subsystems of a smart city system that deal with pollution in the urban environment. We are in an era in which environmental concern is high for many, and the least cost path problem is of interest in a variety of areas, especially when analysing issues related to traffic. Given that road traffic is one of the major air pollution contributors [227], the relevant parts of a smart environment subsystem are considered, which will direct the focus on green infrastructure and its potential to reduce air pollution. It is obvious that the integrative approach must have a holistic vision integrating all components, but in the context of this thesis, the chapter wishes to test the integration of two specific components of a smart city system and therefore takes as a starting point the point where information from mobility and environment can work together to inform citizens. In a smart city environment, travellers are proposed routes which would rather minimize the footprint of their travel on the environment. To achieve this, the proposed system presents an option of a route that has higher capacity to remove air pollution to travellers seeking a route. This practice not only displays an integrated smart city system but also highlights the possibility to travel with less impact on the environment since it is helped by green infrastructure in a smart city environment.

5.2 Background

It was observed that with eco-routing, adopted approaches in previous work focused on reduction of fuel consumption [228–230] by proposing routes that would optimise energy consumption and emissions. In this chapter, we agree that the eco-routing practice has potential to reduce fuel consumption and harmful pollutants generated by mobility; however, we also believe that there is a necessity to remove emitted pollutants from the air. One limitation of our approach may be that we only consider the air pollution removal aspects of the vegetation cover; nonetheless, we acknowledge that the tree cover at route scale provides many other ecosystem services like temperature reduction, shading, amenities, etc. [231,232]

5.2.1 Air pollution removal by trees in smart cities

The removal of particulate matter and other air pollutants is an ecosystem service offered by vegetation and green infrastructure. They can absorb gaseous pollutants through their stromata and intercept particulate matter on their surfaces. The work presented in this chapter focuses on trees since they can provide greater pollution removal potential [233], especially in proximity to the road environment (<50 M; [227]), where concentration of air pollution from traffic vehicles is the highest [227]. Therefore, this work considers this distance and makes reference to [234] to quantify the capacity of a route to remove air pollution.

5.2.2 Smart routing in support of air pollution removal

More than 60% of the European population live in an urban areas [235]. Mobility challenges in urban areas are generally affected by increased travel times due to congestion, which increases fuel consumption and pollutant emissions [228]. Cities always try to find responses to congestion and air pollution by improving vehicles and making travel more efficient. There are now many tools that advise travellers of the efficient routes to take to reduce the duration of travel. These tools generally use a global positioning system (GPS) and mapping—routing software, vehicle speeds on different roadways, and real time traffic information—to advise a least cost path to a particular destination. A ‘‘least cost path’’ in general means a path that minimises emissions. Efforts have been made to develop eco-routing navigation systems to minimise fuel consumption and emissions [228–230]. However, although in some cases the shortest distance takes the shortest time and minimum fuel consumption, it has been argued that shortest distance does not always imply shortest travel time and that the least polluting route was not always the fastest route due to factors such as congestion [228]. This was explained by [236], who highlighted a nonlinear relationship between travel speed and vehicle fuel consumption and emissions. There has been a big focus on how to minimize vehicle fuel consumption/emissions [230]. Many approaches that attempt to minimise traffic emissions through eco-routing can be found in the literature and all these approaches try to reduce air pollution by minimising energy consumption [228–230,237]. However, more can be done not only to minimise emission and air pollution but also to use green components to reduce air pollution. This work closes this gap by presenting a smart city system that favours information integration. This practice consists of integrating information from all the subsystems of a smart city system to get a comprehensive set of information as shown in Figure 5.1.

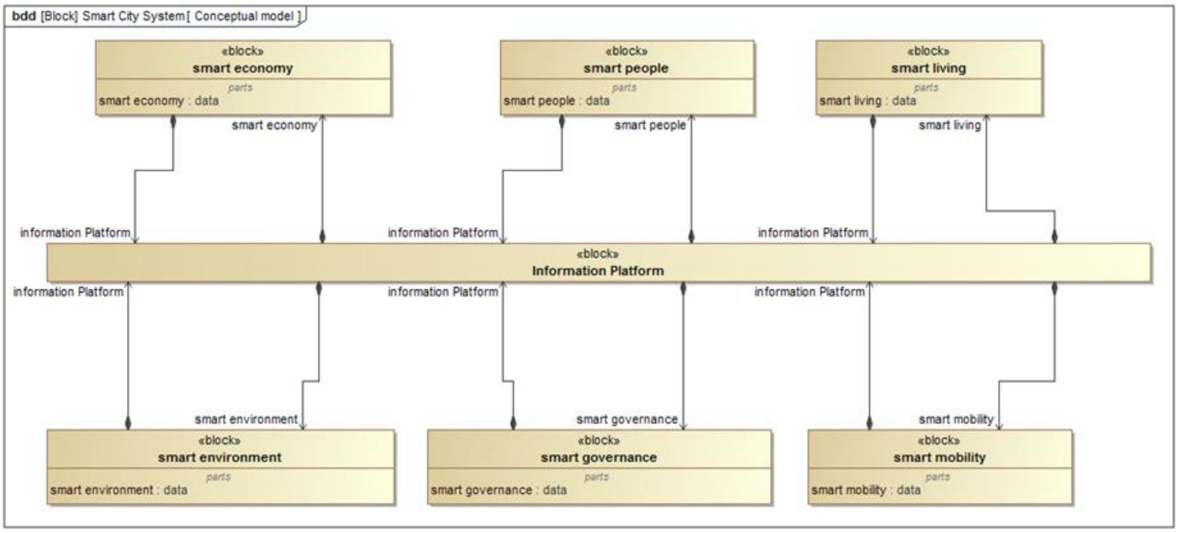

Figure 5. 1 Conceptual structure of an integrated smart city system (Adapted: [26])

There is evidence of a growing demand for both system integration of the smart city system and solutions to deal with pollution generated by traffic [13]. This chapter proposes a solution that is helped by combined information in a smart city on green infrastructure and vehicle smart routing to contribute to air pollution removal from the air. Although actions such as carpooling, electric vehicles (EVs), autonomous vehicles (AVs), and others such as eco-routing can minimise automobiles' fuel combustion and reduce air pollution, it is also essential to extract these harmful pollutants from the air for the benefit of all green infrastructure users.

5.3 Materials and Methods

This section elaborates the adopted vehicle smart routing system approach, a system that integrates information to enhance its significance. It combines air pollution removal by trees and builds on current vehicle routing practices to present a new perspective on vehicle routing systems that considers information integration in a smart city system.

5.3.1 Working approach

The approach towards the new proposed vehicle smart routing system is presented in Figure 5.2. Often, a review of literature presents eco-routing navigation systems that could minimise pollution emitted but that does not remove it. The approach in this chapter is to provide integrated information about the potential of trees to reduce air pollution through smart routing. A combination of route characteristics and green infrastructure produces a smart routing system that rather valorises air pollution removal by green infrastructures.

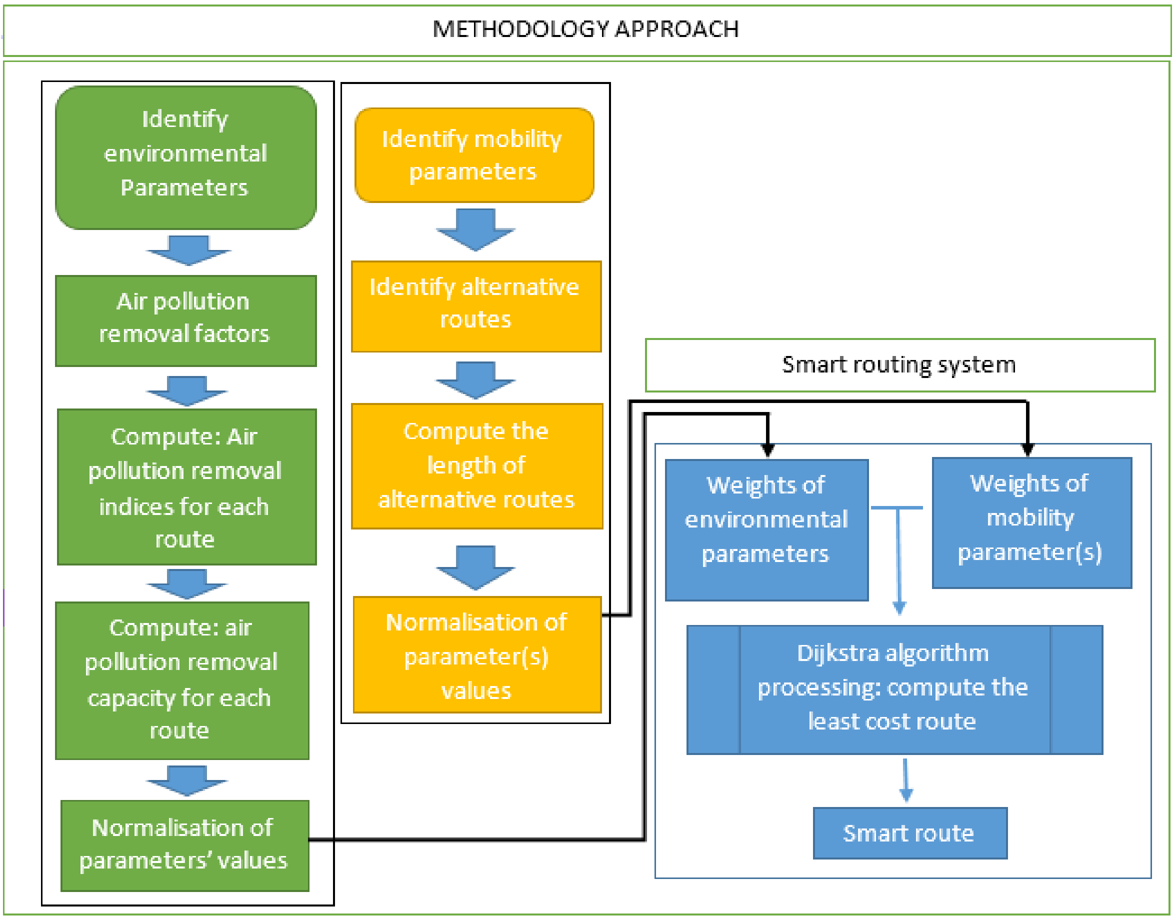

Figure 5. 2 Vehicle smart routing system workflow.

Three tasks are performed in Figure 5.2, where processing of environmental information is presented in green and mobility information processing is presented in yellow. Both green and yellow column results, after processing, give weights with which the smart routing system combines to identify the least cost route (presented in blue). With a weighted graph (Figure 5.3), an algorithm will compute a smart route to be advised to travellers who are frequently faced by the problem of finding the least cost route while planning their trips.

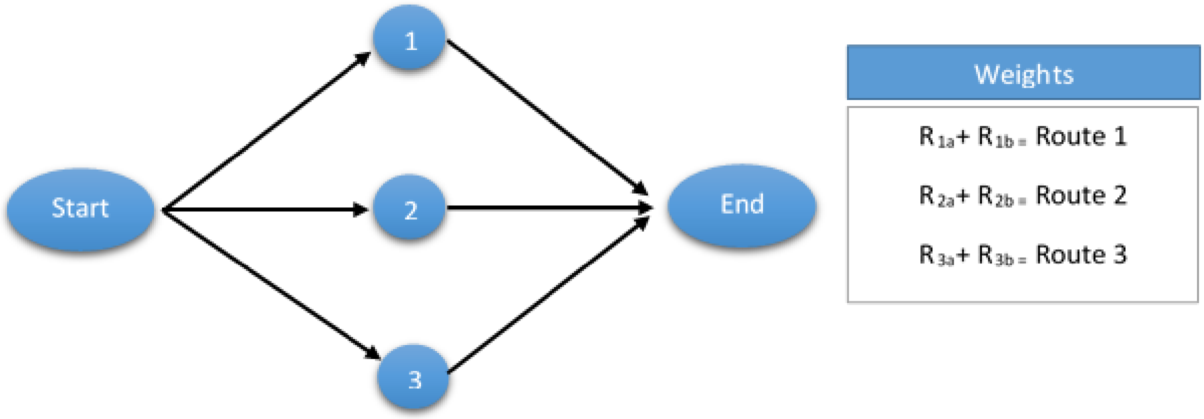

Figure 5. 3 Representation of alternative route on a weighted graph.

5.3.2 Study area

Strasbourg, a city located in northeast of France on the border with Germany, was the study area for this work due to the availability of robust and relevant datasets. It is the largest city and capital city of the Grand Est region. It was estimated that, in the city of Strasbourg, commuting trips produced up to 629.23kg per commuter per year of carbon dioxide. This required 28.90 trees for each passenger to compensate for carbon dioxide production [238].

5.3.3 Data used

To perform quantification of air pollutants removed by trees while following a particular route, there was a need for green infrastructure and mobility data for such a task and air pollution reduction rates computed in [234]. Vegetation (i.e. tree cover) data were obtained from Open Data Grand Est official website (accessed in January 2020). More data concerning environmental parameters were obtained making reference to [234]. For mobility data, distances between points were obtained through analysis in ArcGIS.

5.3.4 Air pollution removal

The reduction of air pollution, which is an ecosystem service produced locally by vegetation, was included in this study. Following the literature [233,239], the assessment of this service at a local scale was based on an up-down approach crossing spatial data (i.e. tree cover) extracted for our route sample and data from place-specific literature to quantify the total amount of air pollution removal per route.

A study by Selmi et al. [234] performed air pollution removal quantification where, in a period of non-precipitation, an i-Tree Eco model dry deposition module [238,239] was used to estimate the removal rate of air pollutants. The i-Tree Eco dry deposition module was used to estimate pollution removal throughout the year and determined reduction rates of air pollutants by trees as follows: NO_2: 0.92 g m^{-2} of tree cover $year^{-1}$, O_3: 3.73 g m^{-2} of tree cover $year^{-1}$, PM_{10}course: 0.79 g m^{-2} of tree cover $year^{-1}$, and $PM_{2.5}$: 0.3 g m^{-2} of tree cover $year^{-1}$. These reduction rates were used for this work as they were obtained in the same context as the study area. A start and end point were selected randomly in the study area to represent an origin and a destination, which allowed for the identification of possible and relevant alternative routes. In general, route network navigation tools are digital maps of routes created in a Geographic Information System database in which user interfaces allow users to input origin and destination information to find a route. Note that the routes studied are the routes defined based on the start and end points chosen randomly. More routes are possible but these three are more realistic routes in terms of distance separating the two points.

In reference to [228], and given that the main objective of this work is more integration of information in a smart city rather than the development of a routing system, random selection of origin and destination information was found acceptable. In ArcGIS, a buffer zone was elected within the near road environment (<50 m), and vegetation cover could be obtained for each route, which represented the canopy cover. The canopy cover and air pollution reduction indices allowed to compute air pollution reduction capacity for routes (Equation (5.1)).

$$C_r = E_i * C_{cr} \tag{5.1}$$

Where C_r is the capacity of a particular route to remove air pollution, E_i is reduction indices for specific pollutant, and C_{cr} is the canopy cover of an individual route (r).

Since air pollution removal quantification was based on place-specific literature, no information was found about air pollution removal by species in Strasbourg city. We were limited to reduction rates assessed within Strasbourg city, like it has been done in New York and Melbourne Results and discussion [233,239]. Note that, for relevance-wise, the i-Tree UK version exists in terms of tree species, Ei etc., however, Since the French case could be more similar to the UK one, it was chosen due availability of inputs required to perform the required task.

The development of the system model of the smart routing system (Figure 5.4) make reference to Figure 2. It shows the flow of information in a smart city system where external sources associated with specific smart subsystems fetch and feed-in specific data, mobility and environmental data in the case of this study, to be processed into meaningful information and later combined at the level of the smart routing system to assign a route.

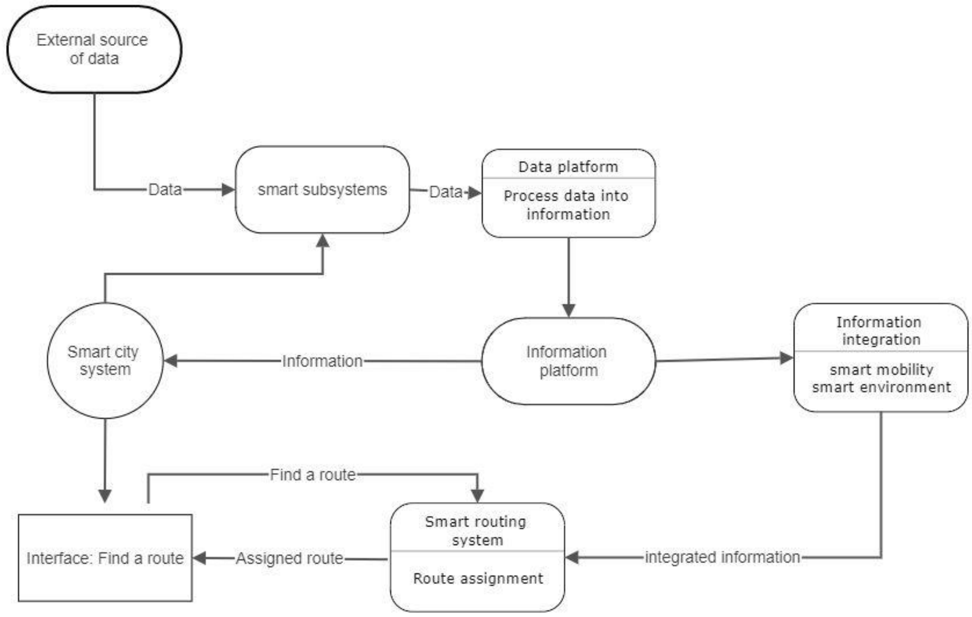

Figure 5. 4 System model of the smart routing system**.**

Various algorithms such as Bellman–Ford algorithm, the Floyd–Warshall algorithm and the Dijkstra algorithm, among others, can be used for calculation of the least cost route [240]. In this work, the Dijkstra algorithm is used to compute the least cost path in a set of alternative paths [240]. This algorithm was considered for this work because, in addition to being the most used in vehicle routing and other network connection protocol, it is easily implemented in a distributed way, and its results contain information on vertices of the entire network, not only vertices they are connected to [240,241]. Traffic problems are dynamic and can change rapidly. This algorithm enables us to compute shortest paths to all destinations from a source instead of just for a specific pair of source and destination nodes at a time, which is very useful in our problem, especially for the complex routes. Provided with good data, the Dijkstra algorithm can be useful for analysing a least cost past problem and proposing a solution (Figure 5.5). The Dijkstra algorithm cannot accept a multigraph (which is permitted to have multiple edges or parallel edges between the same end nodes). Without loss of generality, to solve this problem, the multigraph is converted to a simple graph, which is an acceptable input format for the Dijkstra algorithm, by adding the virtual nodes (showing different route options) between the source and destination. This conversion can be done on any graph input with multiple nodes to find the optimal solution with a lower computing time. In the Dijkstra algorithm, a weighted graph with a source node (start), the algorithm computes the least cost path to a destination node (end) (Figure 5.3).

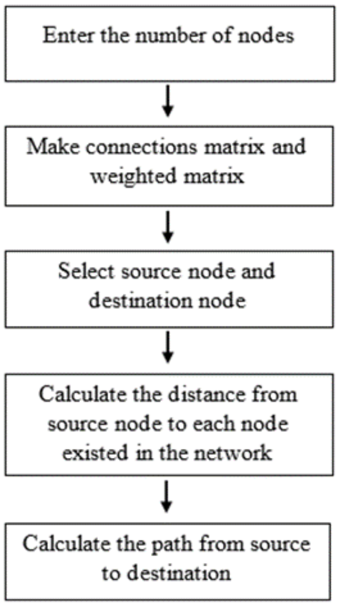

Figure 5. 5 The Dijkstra algorithm flowchart (source: [242]).

Considering the case in which there is a presence of more than one parameter, which is the case for this work, the same algorithm can be used to compute the least-cost route in a set of alternative paths taking into consideration all parameters. This work proposed a combination of mobility and environmental parameters to support decisions on the least cost route in an integrated smart city environment. This definitely plays an important role on choices made by a traveller while navigating on transportation road networks. Users of the transportation network have preferences such as avoiding toll roads, long travel time, etc. [228]. Generally, path construction considers a number of vertices in a graph, and finding the least cost route can take numerous inputs based on minimisation criteria such as travel time, distance, fuel consumption, emission, etc. In the case of this work, path construction is based on removal of air pollutants (i.e., CO, NO_2, O_3, $PM_{10coarse}$, and $PM_{2.5}$) and the shortest route in terms of distance. The overall functionality of information integration combines a general routing navigation practice that considers the shortest path and green infrastructure to advice travellers of a smart route from a network, calculated through a weighted graph representing a network of routes. Weights show the capacity for each individual route to remove air pollution. The principle is that by integrating characteristics of routes and green infrastructure information, air pollution produced by vehicles is removed from the air by green infrastructures. Normalisation of values was performed using Equation (5.2) to enable combination of mobility parameters and environmental parameters and generate a weight for each individual route, which in turn allows integrated information to be obtained. In this work, the least cost route has the highest capacity to remove pollutant from the air.

$$\mathbf{x}'_{\mathbf{Env}} = \frac{\mathbf{x}_{\mathbf{ij}}}{\mathbf{x}_{\mathbf{j}}^{\mathbf{max}}} \text{ and } \mathbf{x}'_{\mathbf{Mob}} = \frac{x_j^{min}}{\mathbf{x}_{\mathbf{ij}}} \quad (5.2)$$

Where x'_{Env} and x'_{Mob} are environmental and mobility parameters, respectively, x_{ij} is the particular value of a parameter, and x_j^{max} and x_j^{min} are maximum and minimum values of each type of parameter, respectively.

After the environmental and mobility parameters are normalized, a route cost can be calculated by summing up the weighted normalized parameters as follows:

$$R_i = \sum_{j=1}^{N} w_j \mathbf{x}_{ij} \quad (5.3)$$

Where w_j is the weight of the *j*th parameter. In a multi-objective function, the weight of each parameter can be set by users based on their preferences. Thus, the weight of influential parameters can vary in different applications. As the proposed approach is more interested in environment-friendly routes, we have decided to consider the same influence in our proposed approach. However, if the number of additional pollutants parameters increases in a way that the impact of the distance becomes less, the distance weight can be increased to compensate for this.

Environmental data/vegetation data were analysed using ArcMap, a component of ArcGIS tool, to draw a buffer zone (shown in Figures 5.6 and 5.7).

5.4 Results and Discussion

5.4.1 Results

Information shown in Figures 6 and 7 illustrates the study area and the routes, subjects of this study. Constructed buffer zones shown in Figure 7 allowed us to obtain the canopy cove for computation of tree cover, and the results are shown in Table 1, together with the length of each route.

Table 5. 1. Routes length and corresponding canopy cover.

Routes	Length_(km)	Tree Cover (m²)
Route 1	10.98	203,797.25
Route 2	11.25	202,623.57
Route 3	11.26	206,412.08

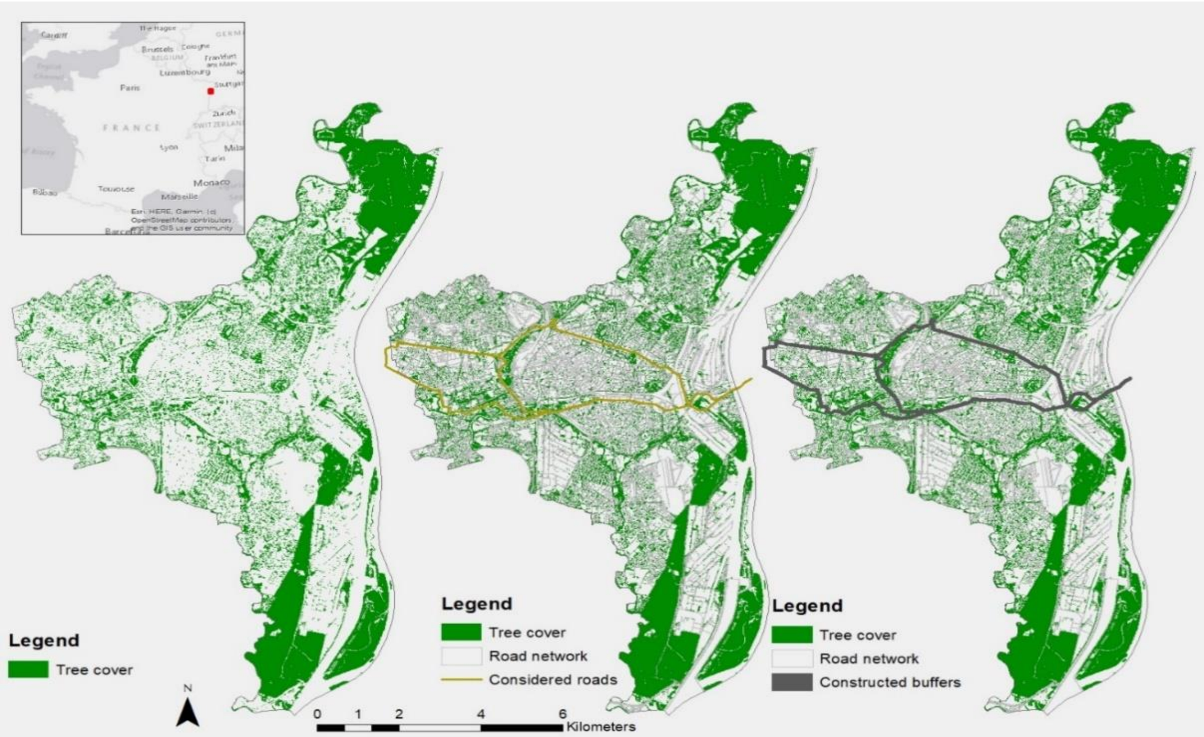

Figure 5. 6 Representation of the studied area, considered routes, and constructed buffers.

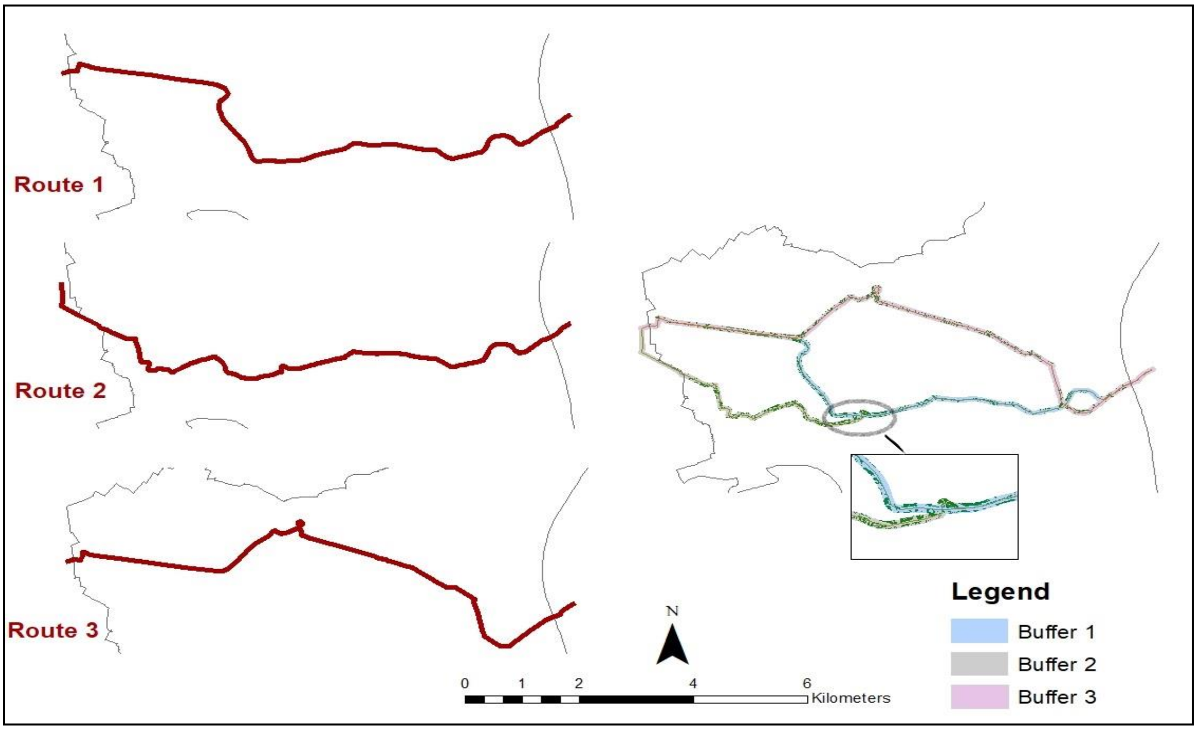

Figure 5. 7 Identification of considered routes and a zoom in on constructed buffers.

Making use of air pollution reduction factors in [234], removal indices were obtained as shown in Table 5.2. The capacity of tree cover to remove air pollution for each route was computed (Equation (5.1)), helped by vegetation data as shown in Table 5.3 in the next section.

Table 5. 2 Indices of air pollution removal by trees (Source: [234])

Removal Indices (g m^{-2} of Tree Cover $Year^{-1}$)					
CO	O_3	NO_2	PM_{10} COARSE	PM_{25}	SO_2
0.08	3.73	0.92	0.79	0.3	0.07

Table 5. 3 Air pollution removal by trees.

	Pollution Removal (g $Year^{-1}$ per Trip)					
	CO	O_3	NO_2	PM10 COARSE	PM25	SO2
Route 1	16,303.78	760,163.74	187,493.47	160,999.83	61,139.18	14,265.81
Route 2	16,209.89	755,785.92	186,413.68	160,072.62	60,787.07	14,183.65
Route 3	16,512.97	769,917.06	189,899.11	163,065.54	61,923.62	14,448.85

The weights presented in Table 5.4 are the results of normalisation (see sub-subsection 5.3.5). The computation made use of Equation (5.2) and each route associated with its individual weights with which the Dijkstra algorithm uses a weighted graph to compute the least cost route with a smart routing system.

Table 5. 4 Values after parameters normalisation and obtain weights of routes.

	Data Normalization							
	CO	O_3	NO_2	$PM_{10COARSE}$	PM_{25}	SO_2	Length km	Weight
Route 1	0.98733	0.98733	0.98733	0.98733	0.98733	0.98733	1.00000	6.92399
Route 2	0.98165	0.98165	0.98165	0.98165	0.98165	0.98165	0.97600	6.86590
Route 3	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0.97513	6.97513

Therefore, by making use of weights computed in Table 4, the proposed smart routing system would select route 3, as can be seen in Figure 5.8.

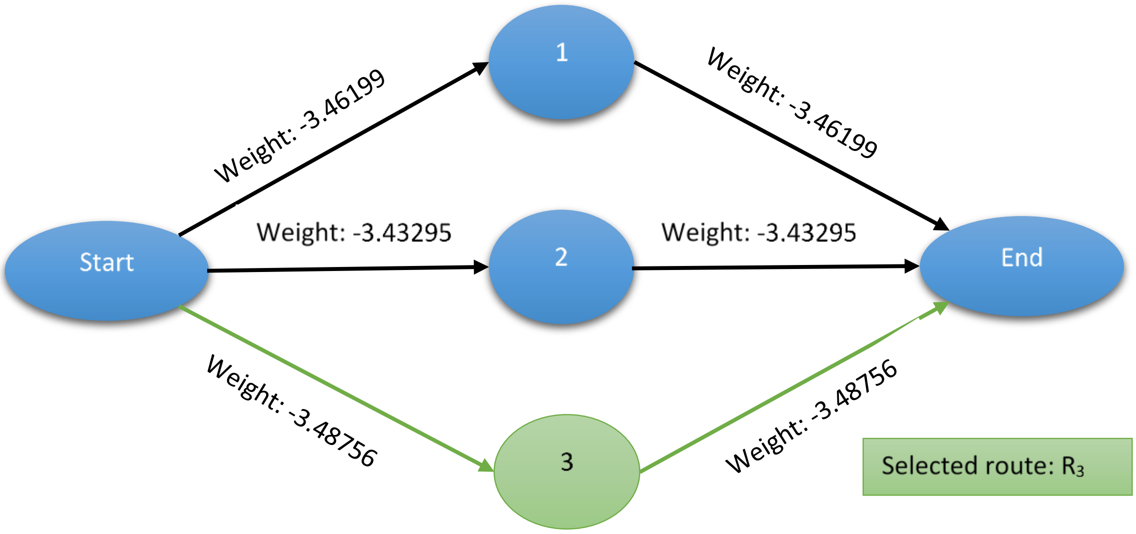

Figure 5. 8 Route selected by the smart routing system.

To make our problem solvable by the Dijkstra algorithm, the initial multigraph (which is permitted to have multiple edges or parallel edges between pairs) needs to be converted to a simple graph without parallel edges. To do this, the virtual nodes can be added as representing the route options while the weight can be divided by two. As the Dijkstra algorithm always finds the path with the shortest value between the source and destination, while we are interested in finding the path with the highest value (higher pollution removal), the values of the edges can be converted to negative to find the correct solution. This approach can be applied to any directed acyclic graph where no negative cycles can be created. Note that the longest path between two given vertices in a weighted graph G (directed acyclic graph) is the same as a shortest path in a graph −G, which is derived from G by changing every weight to its negation. Therefore, if shortest paths can be found in −G, then longest paths can also be found in G. If G is a directed acyclic graph, then no negative cycles can be created, and a longest path in G can be found in linear time by applying a linear time algorithm for shortest paths in −G, which is also a directed acyclic graph.

5.4.2 Discussion

Sections 5.1 and 5.2 showed that, with smart mobility, one of the six subsystems of a smart city system, a lot of work has been done on the mobility of the future (autonomous vehicles, intelligent traffic management, etc). Road traffic is one of the major sources of air pollution and imposes a heavy cost on health and environment. Green infrastructure (urban trees in our case), as an integral part of the smart environment [15], plays an important role in cleaning the air we breathe, and urban trees are one potential solution, among others, to help mitigate air pollution depending on tree cover.

This chapter explored general practices of smart city development and noted that significant work has been done to enable a better understanding of the smart city concept but also observed that existing approaches on the smart city system lacked an integrative view and linkage in architecture [13]. It presented an integrative method that highlights information integration, albeit with extent limited to the focus of this study, in a smart city system which brings mobility information and environmental information to work together and inform citizens.

Green infrastructure is a complementary and sustainable solution to reduce air pollution. Therefore, green infrastructure associated with other integrative strategy measures, such as vehicle smart routing system, can make a significant positive impact on the environment. However, a green road still does not mean a road with less pollutants. Indeed, the morphology of the streets and the leaf density influence (positively or negatively) the nature of the impact of trees on pollution. Trees can also limit pollutant dispersion and thus increase local pollutant concentrations (e.g., near roadways) [243,244], which could exacerbate public health problems due to air pollution exposure. Integrating the impact of trees on air pollution into traffic management systems should be based on in-depth studies of the interactions between urban morphology and the type of vegetation layer. Besides, other indicators, such as vegetation type, age, and condition [245,246], should be taken into account to ensure drivers and the general public's safety. With green infrastructures, a number of more variables come in play such as species of vegetation, leafs area, seasons, etc. To keep focused on the main objectives of this work, parameters which directly helped achieve set goals were considered.

From information in Table 5.1, it is obvious that, if only mobility parameter(s) (distance) is considered, route 1 (R_1) would be selected as the least cost route given that it has the smallest weight. In this case, it is worth noting that for mobility parameters, higher values are non-beneficial, and therefore a route with the lowest associated weight is selected. However, in a smart routing system, where both mobility and environmental parameters were to be integrated (as shown in Table 5.4), the result would be different with a selection of R_3. However, for environmental parameters in this work, the higher capacity a route has to remove pollution from the air, the more it is beneficial and considered.

In general, travellers look for either the fastest route or the shortest route with an objective of travel time minimisation. It is worth noting that, in vehicle eco-routing systems, though in some cases shortest distance minimises emissions, it does not always procure the shortest travel time. This is the same case for smart routing and can sometimes present constricting solutions. Taking a smart route that maximises removal of air pollution from the air does not always guarantee the shortest route or shortest travel time. Results in Table 5.1 and Figure 5.8 expose these facts. If consideration is only given to distance to be travelled, then R_1 is the route to be chosen in contrary to R_3, which is chosen by considering both mobility and environmental parameters.

While the presented solution in this work allows for the removal of air pollution from the air, under certain conditions such as peak times, incidents on road networks, and work on road networks, a side effect of the proposed solution could be that more vehicles are directed in areas such as residential areas, which could have an impact on the already existing concern about air pollution effects on public health. Therefore, the routing engine which contains the shortest path algorithm should give the people's dimension of a smart city a special consideration to make sure that the system works for people and improves peoples' lives. Integration of traffic information and green infrastructure in the process of making smart routing systems can be used to make trips by taking into consideration information on the local environment. It is no doubt that smart routing would require real time data to be richer and more efficient. Real time information is the most efficient and reliable way to determine the least cost route, and it is consistent with [240] with regards to determining the fastest route. Highlighting one of the limitations of this research, the least cost path can only be efficiently determined using real time information.

Given that I did not have access to real time data, future work will enhance the smart routing system presented in this work by considering real time information to give a more reliable route. Data limitation can also be observe in the lack fleet composition and associated emission factors.

Our approach integrating traffic information and green infrastructure relied on data availability and the objective of testing the integration of one ecosystem service information in the routing-system. In this context, the potential of trees to provide ecosystem services (or one ecosystem service in our case) is a tool and does not present an outcome. However, I recognize the necessity to construct an integrated indicator of green infrastructure that combines factors like seasonal variation, foliation density (pollution dispersion), tree conditions (drivers' safety), etc.

In this chapter, air pollution removal quantification was based on place-specific literature, and no information was found about air pollution removal by species in Strasbourg city. This information could be provided by the new version of i-Tree Eco which requires an update of the assessment study. Other factors could also be integrated into the routing-system, like seasonal variation, management practices, etc., as means of enhancing the model and simulation presented here.

i-Tree Eco V5 quantified air pollution removal rates based on an urban forest survey in Strasbourg city that was conducted in 2013 and local data collection (hourly weather data and pollution data). To make the implementation of the smart-routing system more efficient at the micro-scale (i.e., roads), a network of sensors could be set up at road level to measure traffic and pollution generated by the transport network. Thus, in-depth analyses are necessary to develop bottom-up simulation models to study the local dispersion conditions and study the impact of trees at the local scale.

5.5. Chapter summary

Mitigating urban challenges is increasingly becoming very important as urban population expands. Transformation of contemporary cities into smart cities is regarded as a potential solution, and many cities around the world have embarked on a journey of transformation from contemporary cities into smart cities. Though the literature demonstrated that the concept can have multiple benefits, it also showed that the existing transformation approaches of contemporary city systems needed solid and integrative views to avoid disconnection of city subsystems. The proposed scenario in this chapter showed how a smart city system could be integrated by focusing on the information perspective and proposed an approach to mitigate air pollution through information integration in a smart city system. The work presented and justified the proposed vehicle smart routing system, a system that combined information from different smart subsystems of a smart city system to compute the least cost route and at the same time enhance information relevance. The combined information included mobility and environmental information. The case study zoomed into smart mobility subsystem and smart environment subsystem information integration. The objective was to consider a particular scenario to give a visual of integration and flow of information through the integrated smart city system and its' benefits. The nature of the presented model in Chapter Four is that information from all subsystems is made available and accessible among them. Data is sourced and processed into meaningful information at the level of individual subsystems and made available for all subsystems on the information platform. The integration process of information happens on the information platform and it is at this level that information is made accessible to all the other subsystems.

Air pollution is one of the major challenges and its long-term health effects include fatal health diseases and global warming, which fuels natural disasters. The proposed technique, which combined and integrated information in a smart city, allows to provide information that helps to reduce air pollution.

The vehicle smart routing system showed that, while vehicle smart routing might not provide the fastest route, environmental cost, with special consideration of contribution to air purification processes, should be given good consideration and not only considered in terms of monetary or time costs. The results of the study in this chapter showed that, in a scenario where there is consideration of environmental cost and air pollution removal capacity of each individual route, travellers would take different routes as opposed to routes proposed by other contemporary eco-routing systems.

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CHAPTER 6

Conclusion and Recommendations

As it was mentioned in Chapter One, this research was designed around three objectives which stressed the main objectives of developing a methodology to model an integrated smart city system. This chapter exposes how the key research objectives were achieved to justify the contribution to knowledge of this research. It also discusses the research limitations and recommendation for future work.

6.1 Conclusion: Individual chapter contribution to objectives realisation

Table 6. 1: Individual chapter contribution to achieve the research objectives: Major contribution (✓), minor contribution (☑) and no contribution (x).

Research content	Objective 1	Objective 2	Objective 3
Chapter 2	✓	x	x
Chapter 3	x	✓	☑
Chapter 4	☑	✓	☑
Chapter 5	x	☑	✓

The first objective of this research was achieved in chapter Two. In a survey of literature performed, the chapter sought to deepen understanding of the smart city concept and attempted to define the concept in the context of this research.

To highlight the perspective of contemporary cities and associated challenges, it was shown that contemporary cities were facing challenges generated by factors such as rapid growth of urban population, rapid urbanisation, etc. and decided to embark in a transformation process with an objective of becoming smart cities. Various issues challenging contemporary cities and motivating the development of smart cities were exposed.

To deepen understanding of the concept, this research found that the concept of smart city emerged beginning of the 1990s and still has no universally accepted definition; the concept is still considered as the best solution to many issues faced by current cities. Some of the many existing definitions of the smart city concept were put to light and analysed which helped to define the concept in the context of this research

Chapter Two also shed the light on the terms used as alternative to 'smart city' to remove the ambiguity. Terms like 'digital city', 'intelligent city', etc. where defined and the chapter showed how they differ and what they have in common with the term smart city. While it was observed that those terms were used interchangeably to the term smart city, it was found not exactly correct because a smart city was more than an intelligent city, a digital city, a wired city, etc.

To understand the process of transformation of city systems into smart city systems, it was found that that a city was a system of systems and six main subsystems were identified as constituents of a city system. Therefore, transformation a city system into a smart city system meant to transform all the six subsystem together as integrated element of a system. However, the existing practices of transformation produced disconnected and unintegrated smart city systems due to the fact that the city system was very complex.

To cope with complexity, systems engineering was identified as a best fit approach and Chapter Three focused on describing the approach and possible methods to cope with the complexity of the city system transformation process and produce an integrated smart city system. The systems engineering (SE) approach was described together with the Model Based System Engineering (MBSE) methods and systems modelling language (SysML). MBSE happened to have many methods and OOSM was chosen for the modelling task in this research to allow make use of the full potential of MBSE.

To achieve the second objective, as described in Chapter One, an initial conceptual model of an integrated smart city system was presented in chapter Three and later was further developed in Chapter Four. The structure and behaviour of a holistic model of a smart city system was presented and its structure and behaviour described. The presented model strengthened the linkage within the smart city system architecture and demonstrated that the developed methodology could bring solution to complexity and unintegrated transformation processes. Using MBSE, SysML, and a Cameo Systems Modeller, the presented methodology sets the stage for how to model a system of a SC and address the necessity to have all its subsystems interrelated, connected and integrated. An initial analysis of the integrated system model was presented in Chapter Four through three scenarios and tested interaction of elements, and verification of how the system responds when subjected to particular events. The model was later was further tested through a case study in Chapter Five where, after exploration of holistic and systematic views and presenting a model of an integrated smart city system in Chapter Four, Chapter Five proposed a scenario which highlighted and tested information exchange across the model through a case study. The case study build on the integration line of thoughts where by having a smart routing system that integrates smart environment and smart mobility information allows to make a more informed decision. The results of the tests showed that in an integrated smart city system, where all subsystems of a smart city system worked together to provided more full information, people made more informed decision, thus, better and more eco-friendly decisions. A combination of route characteristics and green infrastructure produced a smart routing system which rather valorised air pollution removal by green infrastructures.

6.2 Reflection, implication and limitations

Recall that the aim of this research was to develop an integrated model of a smart city using a methodology capable to cope with complexity observed in process of transformation of contemporary city systems into smart city systems, where the city system was observed to be fragmented, lacked interconnections and interrelation among subsystems. Thus, to provide a viable solution to the prevailing integration issue observed in the transformation process of contemporary cities into smart cities. The presented integrated model developed in Chapter Four not only allowed to gather information from all the smart subsystems of a SC system on an information platform which supports multiple use cases, but also showed a possibility to cope with the complexity issue highlighted in [29,167] which led to lack of integration of all subsystems of a smart city systems [23] and system fragmentation [172,217]. It is with an information perspective that the model was further tested, in Chapter Five, focusing on information exchange across the model through a smart vehicle routing system that valorised benefits of green infrastructures and their capacity to remove air pollution from air. While the case study showed how an integrated model of smart city would operate, it also brought an extra benefit that distinguished this work with other existing works that reduced air pollution through reduction of fuel consumption [228–230]. It is through a novel smart routing system presented in Chapter Five that helped remove vehicle air pollution from the air and at the same time gave a taste of the benefits of integration where smart mobility and smart environments together produced more complete and thoughtful information. The benefits of an integrated systems were emphasised by the smart routing system which determined the most air pollution absorbing route by green infrastructure. The results showed that the proposed technique eliminated air pollutant by up to 1.28%, which is equivalent to 209.19 g $year^{-1}$per trip of CO, 9753.32 g $year^{-1}$per trip of O_3, 2405.64 g $year^{-1}$per trip of NO_2, 2065.71 of $PM10_{course}$, 784.44 g $year^{-1}$per trip of PM25 and 183.04 g $year^{-1}$per trip of SO_2.

Therefore, the chapter Four of this thesis showed an integrative view rather than thematic view, as observed in Chapter Two of this thesis, and Chapter Five exposed the benefits of having subsystems of a smart city system integrated through a case study applied to the new methodology that valorised a holistic view of a city system and showed that the smart city system integration was not only an necessity but had significant benefits.

The presented integrated model create new opportunities for city leadership. Though current practices answer some of the current challenges faced by contemporary cities, the sustainability of such doing is questionable. A sustainable vision would be the best approach such as the adoption of the presented systems engineering approach which support integrative views to better control the city system transformation into smart city while allowing control of changes, improving traceability from requirements and subsystems interactions among them. As it is presented in this research through the developed model, an integrated system becomes a source of more rich and valuable information from multiple sources which is made available directly to all stakeholders. All this implies that better informed decision/policy makers and the general public make even better decisions at all levels in a city.

While MBSE and SysML address system issues such as system completeness, specificity, integrations, verifications, traceability, etc., as well as issues arising from document based approaches, notable limitation in the context of this work concerns lack some capability to execute complex mathematical expressions which might be needed further in the development of the model. MBSE and SysML provide a structured approach needed for systems which complex and multidisciplinary but co-simulations with other tools such as MATLAB can be a good solution.

6.3 Recommendations for future work

There are numerous potential research strands related to this work that would further extend smart city system model understanding and integration:

- More directly, the next contribution would detail more the described MBSE methodology for smart city system integration focusing on the internal structure and architecture to facilitate the city system transformation by deepening understanding of the internal structure and behaviour of the developed integrated model.
- To shed more light for various stakeholder of the smart city concept and how to holistically transform contemporary city systems, more potential future studies would take further the development, analysis, and verification of the presented methodology to model smart city systems through simulation of more practical and realistic scenarios, focusing on interaction and integration of different subsystems to develop an easy interpretation to stakeholders, to highlight the value of eased communication and to deal with the contradicting views observed in prior research.
- MBSE-SysML integration with other tools, such as MatLab, to perform co-simulation would also be considered for further analysis and validation of the model. Note SysML has limitation and that co-simulation would allow to model complex dynamic systems with advanced engineering analysis tools as solvers. This would certainly initiate new challengers about behaviours, management and simulation of a unified and integrated model of a smart city system.
- Due to the observed large number of definitions of the smart city concept and how it was approached by many researchers, the smart city system has many perspectives. In this research, we focused on the information perspective to develop a methodology that emphasised an integrated system of a smart city system. Future work would consider more possible perspectives for further testing and validation for further validation the integrated system model.
- With regards to the presented smart routing system in Chapter Five, while the presented methodology focused on responding to the main objective and took, as a starting point, combined mobility information obtained through a smart routing system and environmental information focusing on green infrastructure to enrich information delivered to citizens, possible further development of the methodology would focus on

advanced development of the smart routing system by considering historic data and more factors such as characteristics of routes and traffic performance measures of routes, etc.

- The presented work in Chapter Five showed that much work remains to be done to achieve a mature system using a wider range of real time data and involving a complete set of all six subsystems of a smart city system as presented in Figure 5.1. Therefore, potential future would consider real time information to take testing and validation of the proposed vehicle smart routing system to another level of accuracy and reliability for all citizens in general and decision makers.

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Appendices

Algorithm Adopted Dijkstra algorithm for vehicle smart routing:

```
//initialisation
Creating the distance graph G
G* = CONVERT(G) //Converting the multigraph G into a simple graph G*
-G* = NEGATIVE(G) //Converting the simple graph G* into its negation -G*
V := Number of vertices in the graph -G*
Define dist[V] as an array which holds the shortest distance from source to each
node i
Define pre[V] as an array which shows the predecessor of node i in the shortest
path to source
dist[src] = 0; // Distance of source node from itself is 0
create node set Q

// Initialize all distances as infinite and pre[] as none, and add each node to Q
for each node i in -G* do
    dist[i] = infinity;
    pre[i] = NONE;
    add i to Q;

// Find shortest path for all nodes
while Q is not empty do
    int u = minDistance(dist, Q); // Pick the node in Q with minimum dist[i]
    remove u from Q
    if u = destination then stop;
    // Update dist value of the adjacent nodes which are still in Q.
    for each neighbour v of u do
        newdist = dist[u] + DISTANCE(u, v)
        if newdist < dist[v] then
            dist[v] = newdist
            pre[v]      = u

return dist[], pre[]
```