2022

A Framework for Designing Blockchain Systems in a Smart City Setting

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A DISSERTATION

Submitted to the faculty of the University of Alabama at Birmingham,
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

BIRMINGHAM, ALABAMA

2022

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ABSTRACT

As main characteristics of successful smart cities, the high demand for increased data security and accessibility and citizen engagement mean the role of blockchain technology has begun to increase. Nonetheless, blockchain technology also faces several challenges, which have slowed its adoption. In response, this dissertation introduces a framework for designing blockchain systems in a smart city setting and considers the smart city and blockchain challenges. Researchers have proposed several smart city models that study and analyze the complexity of smart cities to improve city security, functionality, services, and smartness. The proposed information-theoretical modeling approach to generate an innovated blockchain model in a smart city setting.

This work relies on the following previous modeling investigations: PArchitect, Conant's method, and the least action principle (LAP). Utilizing all of these techniques and organizing them within a framework in the best possible way will improve the blockchain systems in smart cities. We utilize the universal information-theoretical modeling approach and other techniques developed by Dr. Murat M. Tanik and his team. They have successfully developed an excellent modeling technique that plays a significant role in modeling complex systems.

The framework begins with the PArchitect step, which is followed by a Conant analysis, and concludes with the LAP step. First, we model a real-life system using PArchitect, which is a value-based driven molding technique, then perform analytics with

Conant's method. Conant's method plays a significate role in reducing the complexity level and enabling a profound understanding of the system. This is followed by the LAP step.

The role of the framework is to minimize blockchain challenges. The blockchain is continuously in a trade-off with decentralization, security, and scalability, hence, in-depth analysis is required to optimize the trade-off. We propose to utilize LAP to find the best possible distribution of blockchain full nodes (cluster heads) in a blockchain city. Furthermore, LAP plays a major role in clustering the blockchain network. By applying this framework, we minimize the energy and scalability issues in the blockchain and provide capability continuity after modeling that nearly decomposes them, along with a deep understanding of the smart city systems.

Keywords: model, information theory, smart city, blockchain

DEDICATION

I would like to dedicate my dissertation to my parents, wife, siblings, and son for their support and encouragement.

ACKNOWLEDGMENTS

My express gratitude goes first to my committee chair and advisor, Dr. Murat M. Tanik, for his continuous passion, support, and guidance in accomplishing this work. He was always there when I needed him. In addition, I would like to thank my committee co-chair, Dr. Leon Jololian, for his excellent guidance and input into this work. I am also thankful for and appreciative of the encouragement and guidance of my committee members: Dr. Buren Earl Wells, Dr. Karthik Lingasubramanian, and Dr. Mohammed R. Haider.

In addition, I would like to thank Dr. Fuad Sobrinho and Dr. Oscar Pacheco for their time and effort in instructing me in the PArchitect software and their support during the development of the case study. Finally, I would like to thank my incredible team, Mr. Lipscomb and Eng. Alharthi.

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LIST OF ABBREVIATIONS

CJP	Community Justice Programs
CM	Case Manager
CPS	Cyber-Physical Systems
CW	Case Worker
EHR	Electronic Health Records
GDPR	General Data Protection Regulation
HIPAA	Health Insurance Portability and Accountability Act
ICT	Information and Communications Technology
IoT	Internet of Things
LAP	Least Action Principle
MIS	Maximum Independent Set
P2P	Peer-to-Peer
VBPMN	Value-Based Business Process Management Network Model

CHAPTER 1

INTRODUCTION

In smart city modeling, a lack of smart city information and unmanageable size leads to high systemic complexity. The primary role in modeling a smart city is successfully simplifying and idealizing the complexity that underlies the system. Thus, information theory is appropriate to solve these issues since it provides techniques essential to managing information [1]. We propose an innovative technique to model and analyze smart cities by designing the perfect blockchain system. This chapter introduces the background, research statement, and contributions of this research.

1.1 Background

Modeling a smart city poses a significant challenge due to the techniques, visions, and contextual variety involved. For example, the definition and model of the smart city are usually driven by a specific context. Therefore, smart city scholars address the smart city as a system of systems and a complex system [2, 3, 4, 5, 6, 7, 8, 9]. In addition, the smart city evolution shows that the complexity level of a smart city is increased. Thus, understanding complexity is a crucial part of understanding the smart city domain. In addition, considering complexity is a conclusive way to create smart city models and evaluate other such models.

Nowadays, complexity in technology, business, and healthcare domains, to name a few, surrounds us. This complexity is a vast domain of its own and emerges when objects are intricately intertwined and face the limited resource problem. According to Chu et al. [10], the shared denominators of complex systems play a significant role in the realization of complex systems. Unfortunately, complex systems are a broadly interdisciplinary field, making the field difficult to understand [11].

Understanding, predicting, and controlling a phenomenon are the "Holy Grail" of complex science [12, 13], thereby helping to develop general dynamic theories to study living systems in the complex domain. Consequently, many such theories have emerged: information theory, dynamical systems theory, systems theory, complex systems theory, computational complexity theory, graph theory, game theory, and social systems theory [14]. Chapter 2 of this dissertation examines complexity science, which includes the history of complexity science, complexity theory, the complex problems domain, computational complexity, measuring complexity, complex systems, context, and decomposition.

Constructing system models in science and engineering domains is essential for successful research. System modeling is considered to be a multidisciplinary study [15], and modeling complex systems is another level of modeling. In addition, models are an effective way to understand natural phenomena. Nonetheless, the popular models have weaknesses because they are based on many assumptions; these assumptions may be a reason for models failing in particular cases. The axioms should be valid under all circumstances, and, in this regard, the least action principle (LAP) is valid under all circumstances, according to Winchester [1]. Chapter 3 is the modeling chapter in this dissertation, covering system modeling, mathematical modeling, model properties, information theory, system modeling and analysis using LAP, Conant's analysis, the value-based business process management network model (VBPMN), and PArchitect. We based our modeling methodology on the previous studies shown in Fig. 1.

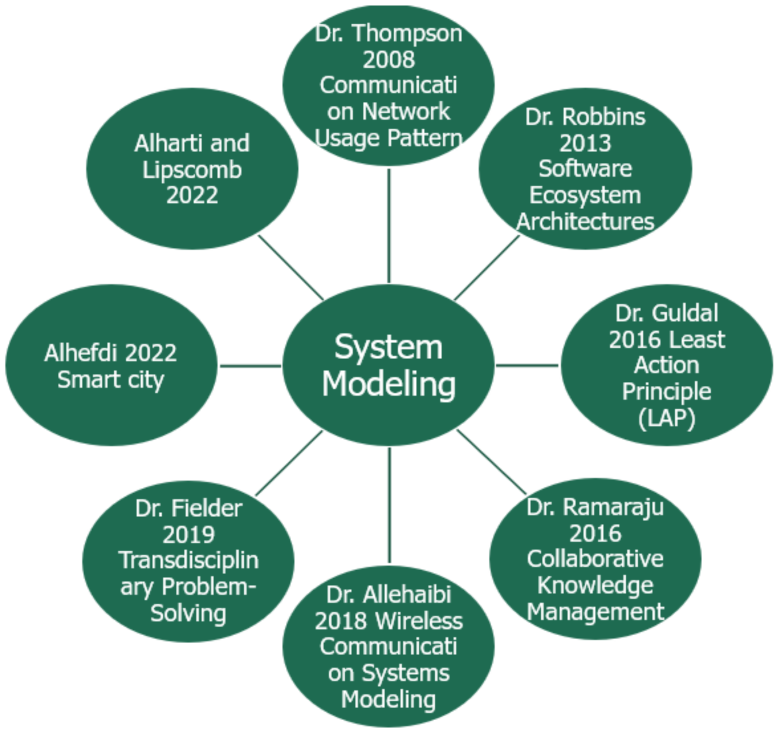

Fig. 1. Previous system modeling studies.

In the smart city domain, several smart city models exist. The critical challenge is constructing a model with capability continuity after modeling for blockchain systems in a smart city setting. Complexity has a significant impact on preventing the smart city model from appearing with capability continuity after modeling. Each smart city has its own goal, context, and vision, hence, researchers have proposed several smart city models. Chapter 4, the smart city chapter, covers the evolution of the smart city, along with its definitions, generations, models, classes, dimensions, characteristics and components, architecture, requirements, challenges, and assessment. Fig. 2 illustrates the evolution of smart city research. The numbers represent the number of abstracts containing the term “smart city” from four popular databases, namely IEEE, ScienceDirect, the ACM Digital Library, and Academic Search Premier. These numbers were current as of February 21, 2022.

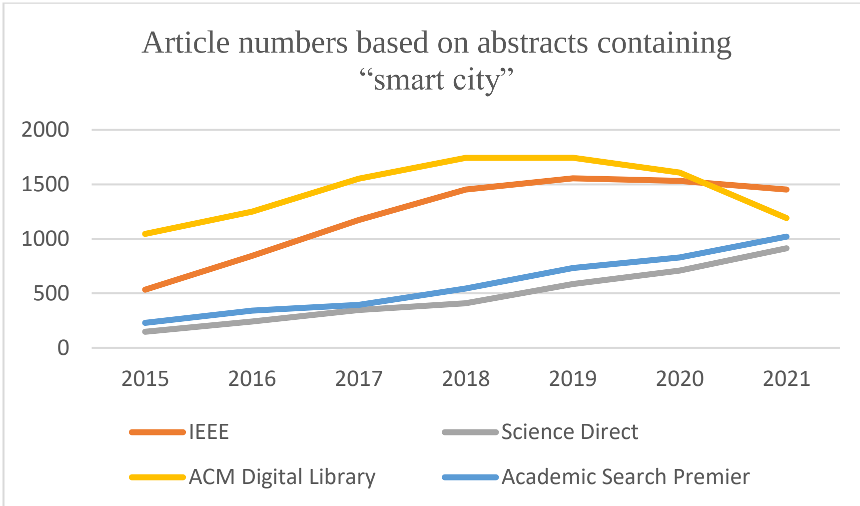

Fig. 2. Article abstracts containing "smart city."

Undoubtedly, information and communications technology (ICT) has played a significant role in the evolution of the smart city. However, a historical overview of the smart city domain shows that the term "smart" has been replaced with different terms such as electronic, virtual, web, digital, information, ubiquitous, intelligent, and wired [16], which illustrates the importance of the technology dimension for a smart city. Smart cities have recently also adopted blockchain technology in several sectors such as healthcare, logistics, mobility, energy, governance, industry, households, and education. Accordingly, the term "blockchain city" appeared in 2018 [18]. Moreover, smart city researchers have clarified the important consequences of the blockchain for individuals, which have led to improved security, trust, and participation [17].

Blockchain technology in smart cities (blockchain cities) is explained in detail in Section 5.7 in Chapter 5. Fig. 3 illustrates the blockchain in the evolution of smart city research as of February 21, 2022, based on IEEE, Science Direct, the ACM Digital Library, and Academic Search Premier databases.

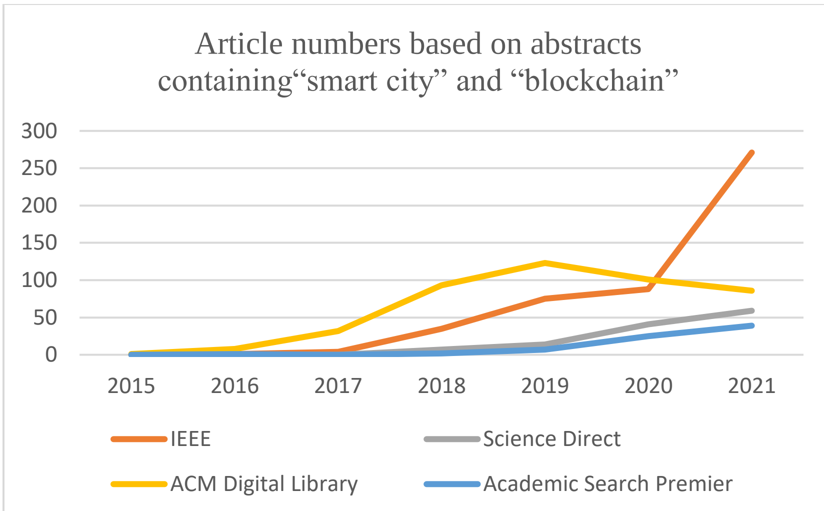

Fig. 3. Article abstracts containing “smart city” and “blockchain.”

In some organizations, a trusted third party is needed. Therefore, these organizations use a centralized structure (e.g., a bank). Unfortunately, centralized systems present several security, reliability, and performance concerns. In this regard, Alharby [19] addressed unauthorized modifications as a security concern, single point of failure as a reliability concern, and bottlenecks as a performance concern. These and other concerns have motivated the emergence of blockchain technology. The main reasons for using blockchain systems are to decrease the presence of centralized parties and improve security and accessibility [20]. Fig. 4 illustrates the evolution of blockchain research, based on IEEE, Science Direct, the ACM Digital Library, and Academic Search Premier databases. These numbers were current as of February 21, 2022.

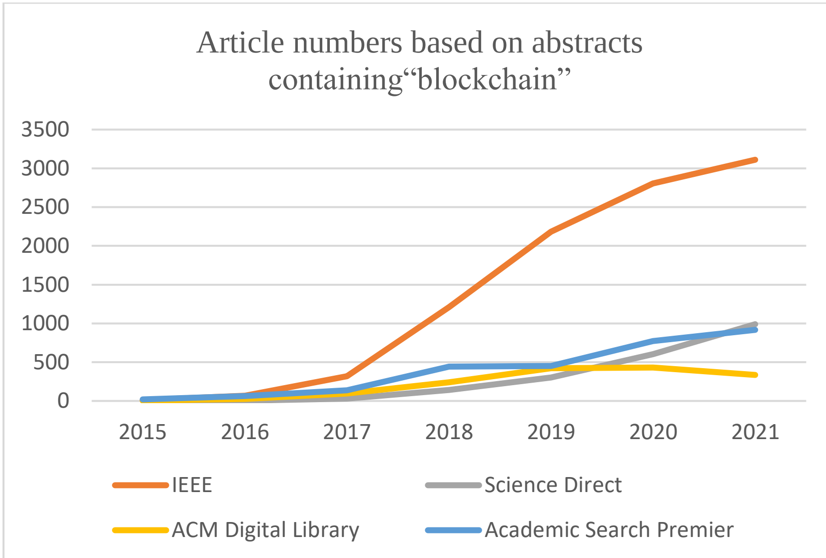

Fig. 4. Article abstracts containing "blockchain."

However, every advanced technology presents its own challenges. Chapter 5 in this dissertation explains the background, definitions, and characteristics of the blockchain; the taxonomy of blockchain systems; the blockchain mechanism; smart contracts; layers of the blockchain; blockchain cities; and the blockchain's challenges and proposed solutions.

We propose an innovative modeling approach using a technique derived from information theory, which can assist in modeling and designing blockchain systems in a smart city setting and minimize blockchain challenges. These are the main contributions of this work. In addition, we undertake an extensive analysis of the blockchain's challenges and limitations in several domains. We address these problems in this work, and they are subsequently minimized by our framework.

1.2 Research Statement

Modeling a smart city is a challenging task. Some smart city scholars have not yet realized the challenges involved. Various smart city models fail to consider the complexity aspect. Modeling complex systems is challenging due to their complexity, context, convergence, and emergence. All these points convey the modeling of smart cities to a different level. In the spirit of convergence, complexity, and context, we deem that smart cities encompass different systems with various contexts, structures, dimensions, and components (mechanical, software, and electronic), which involve complex interactions. Researchers have recently begun studying smart cities as complex systems [21]. Nevertheless, several researchers have continued to model the smart city based on a specific context.

Blockchain technology is already relatively complex. Therefore, applying it to a complex system such as the smart city exaggerates the challenges. In addition, there are several blockchain challenges such as scalability, energy use, time, interoperability, and lack of talent and standardization [22], which are slowing the blockchain adoption process. This work focuses specifically on the scalability and energy challenges, which are explained in detail in Chapter 5. Our framework achieved excellent results in minimizing these challenges.

A smart city has particular characteristics (a.k.a. components): a smart economy, smart governance, smart mobility, a smart environment, smart living, and smart people [2]. We selected a healthcare system in a smart city as a case study to apply the framework. All the aforementioned components play a significate role in developing smart health care. All these components are examined in Chapter 4. The healthcare system is difficult to model and analyze because of its complexity. In addition, healthcare systems have privacy and security restrictions. For example, the Health Insurance Portability and Accountability Act (HIPAA) provides instructions for protecting the client's health information. Nonetheless, using the blockchain in healthcare systems decreases many issues and risks: security, inconsistencies, patient record retrieval, and accessibility [23].

1.3 Contributions

In this study, we investigate the smart city domain from several perspectives. Smart city researchers have typically considered just one of the smart city dimensions (technology, people, and institutions) to be the primary factor in smart cities [24]. As a result, many terms have emerged for each dimension. For example, “digital city,” “information city,” and “wired city” have resulted from considering the technological dimension to be the primary factor in a smart city. In contrast, smart communities consider the institutional dimension to be the primary factor.

Moreover, when the people dimension is the primary factor, terms such as “creative city,” “learning city,” and “knowledge city” appear. In reality, the term “smart city” combines all these dimensions [24]. Researchers who have not considered this amalgamation have also failed to see that the dimensions are intricately intertwined and should be recognized as complex systems [25].

Currently, insufficient modeling of complex processes exists due to the principles of complex systems, of which contextualization is one. Contextual conditions are one of the primary complex engineering challenges, and context also plays a significant role in the smart city domain. Context extends to people and objects and their changing profiles over time [26]. We have considered that in our framework.

We propose a framework to design a blockchain system in a smart city setting. Our framework includes PArchitect, Conant analysis, and LAP. The smart city context, vision, and goal are the principal first steps in the modeling. Our framework modeling begins by understanding and analyzing the interactions of real-world systems and then developing the information flow for the system. If the model needs adjustment, it returns to the system's information flow step until the model meets the validation measures.

The information flow for the system of a smart city model consists of five main steps. Observing and describing the process is the first step in the framework. It can be any context or vision. Then modeling begins using PArchitect. There is insufficient modeling of smart cities as complex systems, and the PArchitect modeling step solves this issue. The modeling section in Chapter 3 details the PArchitect modeling technique. Following this, the Conant analysis step plays a significant role in providing another level of understanding of smart city systems. Therefore, the results of the Conant analysis provide the information required to select the full nodes in the blockchain network of the smart city. Next, these results are rechecked to ensure that the model meets the context or vision of the smart city. In addition, the Conant analysis results are interpreted in conjunction with the observed and described processes in the first step. The system is then converted into a graph to which LAP is applied to find the optimal way to distribute the full nodes on the blockchain network.

Defining the context is essential to the decision-making process [27]. Frameworks and models in a complex domain need to adopt every change that occurs. Additionally, static and inflexible framework results would not be worthwhile because of the lack of certainty and continuous change inherent in complex systems [13]. We consider these challenges in our framework. Our framework models a system that also solves the scalability and energy issues produced by blockchain technology.

1.4 Summary

In conclusion, we propose a framework using an information-theoretical technique to create an ideal blockchain system for a selected system in a smart city setting. The adoption of changes and lack of certainty are considered within the framework, which is then tested in a health care system. As a result of that test, we develop an innovative blockchain city model. This work involves various domains: complexity, modeling, information theory, smart cities, and blockchain technology.

CHAPTER 2

COMPLEXITY

2.1 Introduction

Complexity science is an interdisciplinary science that has emerged from multidisciplinary fields. In complexity science, as previously stated, understanding, predicting, and controlling a phenomenon is the “Holy Grail” [13, 12]. This chapter discusses the complexity domain by examining the history of the complexity sciences, complexity theory, complex problems, computational complexity, measuring complexity, complex systems, context, and decomposition.

2.2 History of Complexity

In the early 1970s, the science of complex systems emerged [28, 14] as an interdisciplinary study that arose from multidisciplinary areas such as computer science, engineering, physics, mathematics, biology, and economics [10]. Tuncer et al. [29] defined complexity as “a lack of information about a system, and unmanageable size means high dimensionality.” The primary role of the science of complexity is to successfully simplify and idealize unrealistic models.

Fig. 5 illustrates the history of the complexity sciences. Castellani and Lasse [14] recently updated the map of the complexity sciences. This map has been frequently used. Generally, the map is an interdisciplinary introduction to complexity science, which illustrates the evolution of complexity and progresses from the 1940s to the 2020s. This map can be read in two ways. The first way is to read from the left to the right. This way illustrates the historical practice. The second way represents the organizational structure. Complexity science involves five main influential traditions [14]: dynamical systems theory, systems science, complex systems theory, cybernetics, and artificial intelligence (AI). These five systems are the second way to read the map [14]. This section details the historical view of complexity from the 1940s to 2020s, shown in Fig. 5.

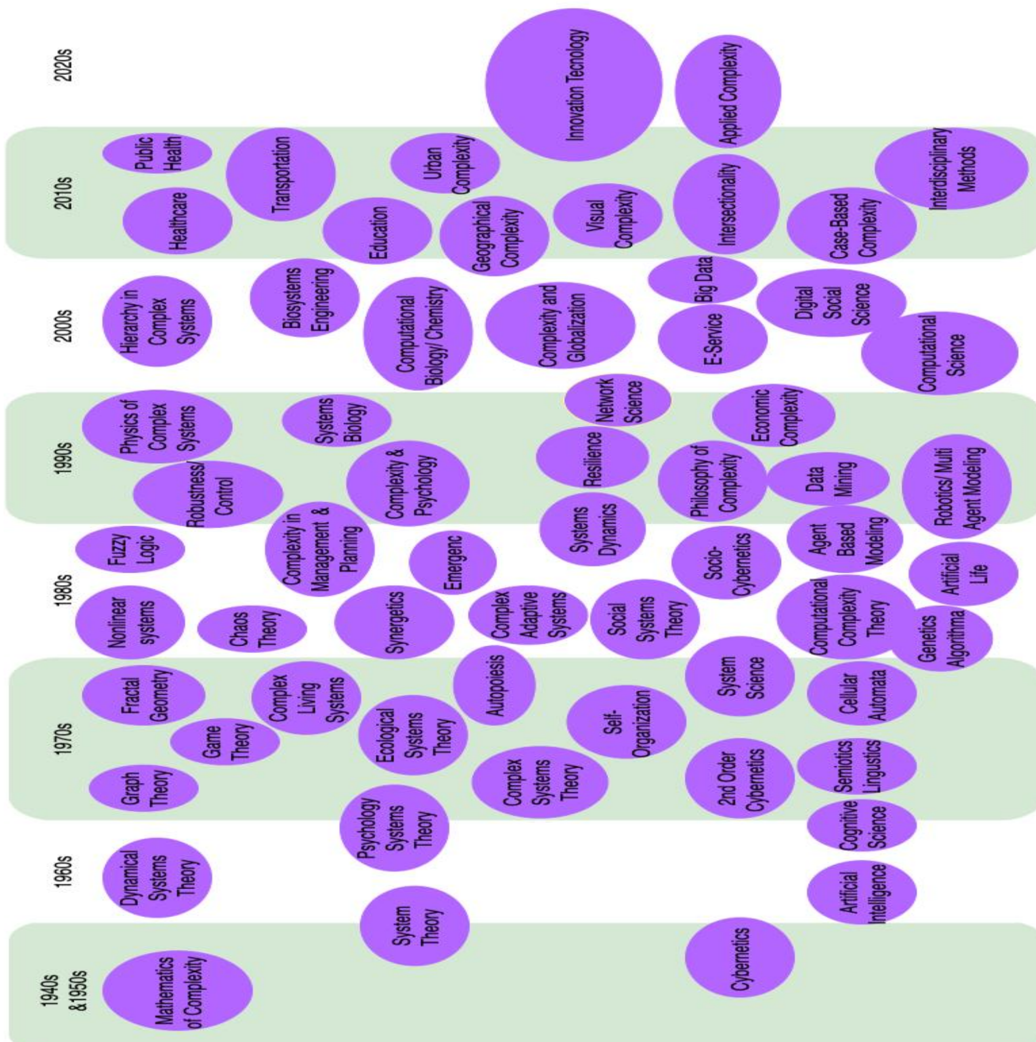

Fig. 5. The map of the complexity sciences [14].

Scientists consider complexity to be a vast domain. According to Chu et al. [10], the search for the shared denominators of complex systems plays a significant role in understanding complex systems. In the 1970s and 1980s, academia and industry showed considerable interest in complexity science. However, complexity is a broadly interdisciplinary field, making understanding complex systems difficult [11]. To understand complexity, we need to return to the 1940s and 1950s. Isaac Newton [1642-1727] has greatly influenced the mathematics of complexity [14]. Newton noticed that the mathematics of the time was insufficient to study the motion of the solar system. The main challenge was the continuously changing direction and speed of the planets in the system. Consequently, he conceived of fluxions, subsequently known as calculus [30].

Cybernetics was of considerable interest to scholars in the late 1950s and the early 1960s. For instance, Norbert Wiener has had a significant influence on mathematical cybernetics. He published several books on cybernetics and the complex domain. Another pioneer in cybernetics and systems theory was William Ross Ashby (1903-1972) [31, 14]. There is no doubt of the significant role played by information theory in cybernetics and the complex domain. According to Winchester [1], information theory provides techniques that are essential to managing information. In addition, entropy plays a significant role in cybernetics and the complexity domain, as defined by Claude E. Shannon [32]. The information theory section further details this role.

As a result of the science of complexity, many theories have emerged. These theories are information theory, dynamical systems theory, systems theory, complex systems theory, computational complexity theory, graph theory, game theory, and social systems theory [14]. Each of these theories has its own well-known contributors. For example, Stephen Smale [1930–] proposed a geometrical way of using classical mechanics to describe the behavior of a dynamical system [33]. He is a pioneer in dynamical systems theory.

Many scholars have also contributed to the systems theory and systems science domains. For example, Ludwig Von Bertalanffy and Ross Ashby were the founders of systems theory in the 1940s and 1950s [14, 34]. Alexander Bogdanov was also a noteworthy scholar and the founder of systems thinking [14]. Bogdanov was a distinguished Russian philosopher and scientist. His concept of "tektology" has become widespread and defined a new advanced science [35]. Tektology is known as the "Universal Organizational Science," which Bogdanov described as "a general study of the forms and laws of the organization of all elements of nature, practice, and thought" [35].

All these scientific achievements made the study of complex systems necessary for the development of science, which, in turn, led to the emergence of the science of complex systems. The science of complex systems features distinguished scientists. For example, Philip Warren Anderson (1923–2020), Warren Weaver (1894–1978), and Per Bak (1947–2002) contributed to the complexity domain and complex systems engineering [14]. Philip W. Anderson was awarded the Nobel Prize in Physics for discovering electron localization [36]. Anderson declared that "a new level of complexity requires new fields, connecting physics, chemistry, biology, computer science, and economics" [36]. In addition, Warren Weaver defined complex systems as "systems where individual parts act independently of each other while still following a set of simple rules. When all these independent decisions are added together, very sophisticated behavior can emerge, and all without any planning"

[37]. Per Bak is the pioneer of the physics of complex systems. He and his colleagues, Tang and Wiesenfeld, published a paper on the theory of self-organized criticality in 1987 [38].

Computational complexity theory has played a significant role in developing the complexity domain. For example, Stephen Cook proposed using a Turing machine in polynomial time to compute complexity [39]. Similarly, Andrei Nikolaevich Kolmogorov (1903-1987), who is considered one of the greatest mathematicians of the 20th century, significantly influenced many areas such as measure theory, set theory, probability theory, the theory of random processes, graph theory, information theory, and complex theory [40]. Other scientists of note include Jay Forrester (systems dynamics), Peter Checkland (soft systems methodology), George Klir (systems engineering), Debora Hammond (systems thinking), and Walter Buckley (complex adaptive systems) [14].

According to Sloot [41], we are living in an era of advanced technology, which allows new vistas into physical, biological, digital, and social processes. To move from individual parts to integrated systems, systems should meet the temporal and spatial orders, which are known as complex adaptive systems. Usually, complex systems are complex dynamic or adaptive systems [42]. These systems feature several characteristics: endless impressions of order, disorder, leaderlessness, self-organization, emergent patterns, non-linearity, and adaptivity [42, 41]. The complex systems section describes complex systems in detail.

According to Chu et al. [10], some complex scientists consider generating a general theory for complexity to be exceptionally difficult, if not impossible. [43] mentioned this challenge and that it remains open [44]. There is also considerable doubt about the significance of this challenge. Complexity researchers consider the task as possible or impossible. In terms of impossibility, there are no “common causes for common characteristics” in a complex system due to the diversity of the domains of the complex system. Scholars from outside the field of complexity science have considered this viewpoint [10].

2.3 Complexity Theory

Today, complexity is inevitable; we find it in different areas such as technology, business, and healthcare. Complexity appears when objects are communicated and face the limited resource problem. The purpose of complexity science is to understand, predict, and control a phenomenon [12, 13], which helps develop general dynamic theories to study living systems within the complex domain. Sometimes a general dynamic theory is described as a “unified theory of complexity.” These theories define the emergence of complexity in areas where entropy is increasing [44]. Guldal [45] defined entropy as “a measurement of the disorder of particles.” The information theory section explains entropy is explained in detail.

Two popular research approaches exist in the complexity domain [44]. First, complexity theories study inanimate and animate systems. Snooks [44] recommends using dynamic theories to explain living systems by using the physics model. Second, all complexity scholars use the physics model for the critical analysis of inanimate and animate systems thus focusing on the supply side. However, they have completely neglected the demand side, which is crucial to understanding and analyzing living systems. Complexity theorists have demonstrated some methods of separating the living from inanimate systems and also adopted the whole demand-supply mechanism in the living system. Because of these two approaches, the dynamic theory is applicable [44].

2.4 Complex Problem Domains

Nowadays, humans face complex problems, which have various behaviors. These behaviors have uncertain independent, changeable, and dynamic consequences [46, 13]. Therefore, uncertainty is an essential factor of complex problem domains. Furthermore, a lack of fixed definitions, prediction difficulty, ill structure, and changeability play a significant role in complex problem domains [47, 13]. Consequently, complex problem solutions are changeable and unpredictable [48].

Although many complicated systems exist, they are not considered to be complex systems [49]. Complexity scholars recognize several basic properties for a problem to be described as complex. Wingo and Tanik [48] proposed that interdependence and uncertainty are the main characteristics of complex problems. The components communicate unexpectedly in complex problems, producing uncertainty and a difficult modeling challenge because of the connection between singular actions and system performance [48]. Pursuing to reveal problems plays a significant role in forming an in-depth understanding of the systems [50, 48].

Stacey's spectrum of process complexity and the Cynefin framework are two popular frameworks addressing problems, processes, and systems that range from simple to chaotic or out-of-control. Stacey developed the spectrum of process complexity, and his central focus was on organizations [48]. In contrast, the Cynefin framework focuses on knowledge management and is described as "a sense-making model" [48]. The Stacey and Cynefin frameworks are explained in the following paragraphs.

Fig. 6 represents the process and problem complexity range introduced by Ralph Stacey. According to Stacey's model, complex problems fill the range between "out-of-control” and “complicated” [13]. Approaching simple and complicated problems is easier than approaching complex problems [51, 13]. The range of the process and problem complexity plays a significant role in constructing models and frameworks for complex environments. These frameworks must adapt to any problem space changes. Conversely, due to the lack of certainty and continuous change in complex environments, the outputs of static and inflexible frameworks may not be beneficial [13].

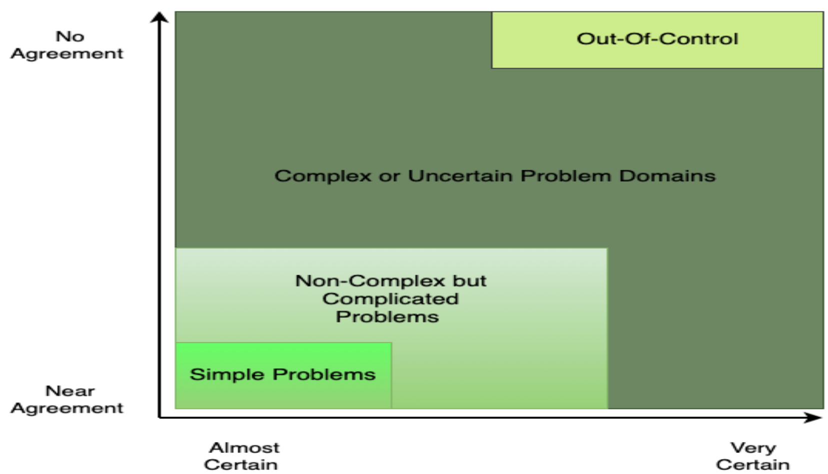

Fig. 6. Range of process and problem complexity [13].

Different contexts exist in the complex domain: simple, complicated, chaotic, or complex [52]. In the modern complex engineering domain, determining the context is essential, especially in the decision-making process [27]. As previously mentioned, contexts have four primary levels: simple, complicated, chaotic, or complex. All of them have different methods of action. For this reason, the Cynefin framework has been used to help executives define the context in which they are operating, which helps them to make relevant decisions [52].

The Cynefin framework helps to perceive the difference between simple, complicated, chaotic, or complex contexts, as shown in Fig. 7. The context defines the purpose of the experiences, systems, or models. The context can be the surroundings, environment, or setting. Two universes exist in the context domain: ordered and unordered. In the ordered universe are simple and complicated contexts, in which the relationships between cause and effect are sensible. In contrast, in complex and chaotic contexts, the relationship between cause and effect is not apparent [52].

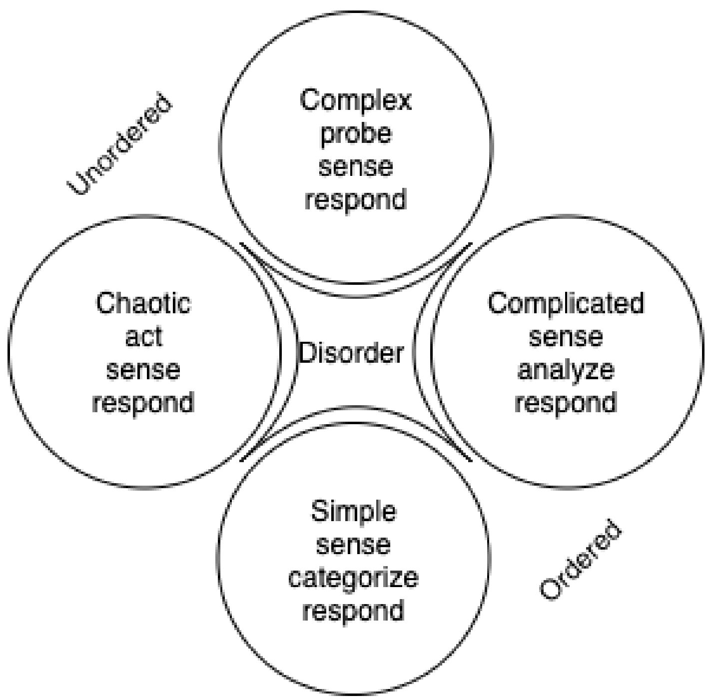

Fig. 7. The Cynefin framework [52].

Some confusion arises in differentiating between complicated and complex systems. Scholars have proposed several models and frameworks to clarify that confusion in the complex domain. The Stacey and Cynefin frameworks are considered the most popular in this area. Table I identifies keywords for complicated and complex problems [53].

TABLE I

KEYWORDS FOR COMPLICATED AND COMPLEX PROBLEMS

Complex	Complicated
Dynamic	Formal, Fixed
Dense interdependencies	Inputs
Alive	Dead
Surprise	Repetition
Humans	Machine
Principles	Rules
Integrated people and operations	Liberate operations from people
Group pressure	Bureaucracy
Nonlinear change	Series of steps
Quickly unpredictable	Predictable outputs
Creativity and innovation required	Expertise required
Uncertainty	A high degree of certainty

Sobrinho et al. [54] mentioned 24 principles for evaluating and modeling complex problems. We explain these principles in detail in the VBPMN section; however, the following sentences highlight some of the principles. For example, the unending principle means that the process continues to emerge and does not stop. The transdisciplinary principle involves the fusion of multidisciplinary engineering information and values to develop the solution. Contextualization plays an essential role in meeting all the likely user contexts, which is what makes modeling complex systems difficult and costly [13]. The context section further explains context and its definition. Ultimately, all these complex principles can be obstacles to achieving the ideal alignment between reality and the model [13, 54].

2.5 Computational Complexity

Computer science defines computational complexity based on classification problems constructed on the computation required to solve the problems. The time complexity must be defined when the computer states the problem can be solved. The size of a problem can play a significant role in the time domain. The measurement of the time required to complete complex processes depends on a particular unit of time. Polynomial algorithms have a significant impact on solving computational complexity. “If an algorithm with time complexity for some inputs is lumped together, it is called tractable” [55]. The problem that an algorithm can solve with non-polynomial time is called intractable. For example, if the problem has a minimum spanning tree, then it is a tractable problem. In contrast, the traveling salesman problem represents an intractable problem [55].

The polynomial algorithm P plays an important role in intractable decision problems. “A decision problem P is an element of the class P if and only if a polynomial-time algorithm can solve it” [55]. Therefore, we can state that a deterministic algorithm is polynomial. Conversely, a nondeterministic algorithm is non-polynomial. “A decision problem P is in the class NP if and only if a nondeterministic algorithm can solve it in polynomial time” [55]. The most potent point of the nondeterministic algorithms is that they detail extensive results in polynomial time. The NP-complete class consists of NP problems, but they have an efficient algorithm that can solve them [55].

2.6 Measuring Complexity

The definition of complexity plays a significant role in solving or studying the mechanisms and history of complex systems because of the current lack of a working definition for the term. There are ways to define the complexity, such as comparing different problems using a numerical scale. However, this method produces unsatisfactory results [56].

Bruce Edmonds mentioned three essential points concerning the complexity measurement in his Ph.D. thesis: complexity depends on the observer, “emergent” levels of complexity, and “modularization with interdependencies” [57]. Complexity depending on the observer means the observer can measure or define the complexity of natural phenomena, but this definition is not helpful because natural phenomena possess some details that the observer will be unable to perceive [56].

The second element is “emergent” levels of complexity. The emergent properties come from unexpected, aggregate interactions between system components. The emergent levels of complexity depend on the observer. The author used the effective example of a mathematical system. This example showed how difficult it is to prove the new branches of the theory. The final element is “modularization with interdependencies.” This element relates to the cyclomatic number using a small and closed graph. The cyclomatic number measures the complexity by representing a tree. The cyclomatic number is used to indicate the complexity of the system [56].

The complexity of a system can be measured by its entropy and transmission rate, regardless of the system's components. Thus, the complexity is associated with the information [29]. Conant [58] proposed an excellent method to measure complexity in terms of entropy, which illustrates the activity of the system's components and whether they act independently or coherently. The Conant section explains his methodology in detail.

2.7 Complex Systems

A system is a compilation of entities that work together to attain a certain goal. However, what makes a system a complex system? In general, the number of components in the system is not a measure of the system's complexity [59]. Instead, a general condition exists that indicates whether or not a system is complex. If we can decompose a system, that system is not considered to be a complex system. Conversely, if the system is not decomposable, the system is complex [25].

There are various key components of complex systems. Johnson [12] explained the role of a system's openness and interactivity with the environment, driven by ordered and disordered behavior, and feedback loops and memory as learning sources. Complex systems are difficult to study and understand through observation only [11]. As a result, at the end of the 1970s and the beginning of the early 1980s, theories from physics and computer science surfaced [14]. Complex systems are an interdisciplinary subject, which means they encompass a broad area. Researchers have proposed a large number of techniques, theories, and ideas for studying and analyzing complex systems and complexity domains in general [11]. These theories are complex systems theory, dynamic systems theory, graph theory, game theory, network science, social systems theory, and computational complexity theory [14]. More details can be found in the history of complexity section.

The structure of complex systems can be divided into two types [59]. This structure is based on the way in which the system has been created. Human interaction plays a significant role in this division. The first type are systems created by humans such as business organizations. The second type are systems that are the work of nature, such as the structures of plants. To clarify the idea, we use a personal computer as an example of a system. A personal computer is an intricately intertwined system. Nonetheless, we can separate each part or mechanism and decompose it. Some of these parts are built upon others, and each is understandable by itself.

On the other side, a communication system is an example of a complex system. Some complex system examples do not involve humans, such as the structure of animal and plants systems. For example, plants consist of roots, stems, and leaves. Every part has a specific structure. Each part has its own complexity.

The observatory perspective plays an essential role in determining the hierarchy of any system. In Grady Booch’s book, *Object-Oriented Analysis and Design with Applications*, he cites the example of astronomers and nuclear physicists, which showed how the observatory plays a significant role in determining the hierarchy of any system. In the astronomers’ case, they study space, stars, planets, and debris. Consequently, their hierarchy will be built based on these elements. On the nuclear physicists’ side, they study elements such as atoms, electrons, neutrons, and other small parts called quarks. Therefore, their hierarchy will be constructed based on these elements [59].

Sometimes, scientists recognize complex systems as complex dynamic or adaptive systems [42]. Boccara [49] defined the dynamical system as “a set of equations.” A complex system has five attributes: hierarchical structure, relative primitives, separation of concerns, universal patterns, and intermediate forms [59]. Lee et al. and Sloot [42, 41] also presented several characteristics of complex systems. They mentioned endless order and disorder patterns, leaderlessness, self-organization, emergent patterns, non-linearity, adaptivity, and stochasticity.

In the five attributes of complex systems detailed by Booch et al. [59], the first attribute is the hierarchical structure. The primary purpose of hierarchy is to analyze and show all the elements or components and their relationships. The second attribute is relative primitives. The third attribute is the separation of concerns. Simon describes the hierarchical system as decomposable [47, 60]. Because we can nearly decompose the system into parts, these parts are described as nearly decomposable because they are not entirely independent [25]. The fourth attribute is common patterns. This attribute reveals the common patterns between some complex systems. Some of them are in small components such as the cells found in both animals and plants and others in large structures such as the vascular system. The last attribute is stable intermediate forms. This attribute explains that complex systems develop over time. In addition, we can state that the complex system evolved from a simple system that worked.

As noted, Lee et al. and Sloot [42, 41] also discussed complex system characteristics. The first characteristic is endless order and disorder patterns. Engineers have proposed solutions to these issues, but they face the complexity that results from entropy or disorder [13]. In communication, entropy occurs as a result of noise, which causes incorrect information to be transformed [32]. The second characteristic is leaderlessness, while third are self-organizing characteristics, which means if the systems have any patterns that emerge, they will be organized without external control. The fourth characteristic is emergent patterns, which are the patterns that occur without directed actions from agents. The fifth characteristic is non-linearity. The nonlinear system is defined by [61] as an "over-approximation of the nonlinear dynamics with respect to the system state around a linearization point x." The feedback loops play a significant role in nonlinear systems. The sixth characteristic is adaptivity. When a system emerges coherently and adapts to new patterns, it is an adaptive system [62].

2.8 Context

Contextual environments are one of the main challenges faced by modern complex engineering. According to Fielder [13], transient environment variables such as the user's location, weather (e.g., temperature, humidity, and rainy), and network and technology status play significant roles in solving complex system problems [63]. Contextuality has a primary role in creating unexpected errors in complex systems [10], which demonstrates how context plays an essential role in affecting the behavior of these systems. This behavior is critical in the modern engineering domain.

Fielder [13] has presented several definitions of context. Context can refer to people and objects and their changes over time and processes [26]. In addition, Brown et al. [64] addressed the location, users' surroundings, time/date, and the weather as contextual. Anind and Gregory [65] defined context as "any information that can be used to characterize the situation of an entity. An entity is a person, place, or an object that is considered relevant to the interaction between a user and an application, including the user and applications themselves."

The engineering context consists of several elements, as shown in Fig. 8. The user's location and type, laws and regulations, ordinances and codes, environmental circumstances, and technology availability and qualifications are the contextual elements in engineering. All of these elements must be considered [13]. Each of the contextual elements has its own classifications. For instance, the user type has several variations, such as young, elderly, rural, urban, or physically challenged. In addition, wet, dry, muddy, humid, seismic, cold, and hurricanes form categories in the environmental circumstances. The law could be state, federal, or international. An engineering solution that does not consider the contextual elements is more likely to be unsuccessful [63].

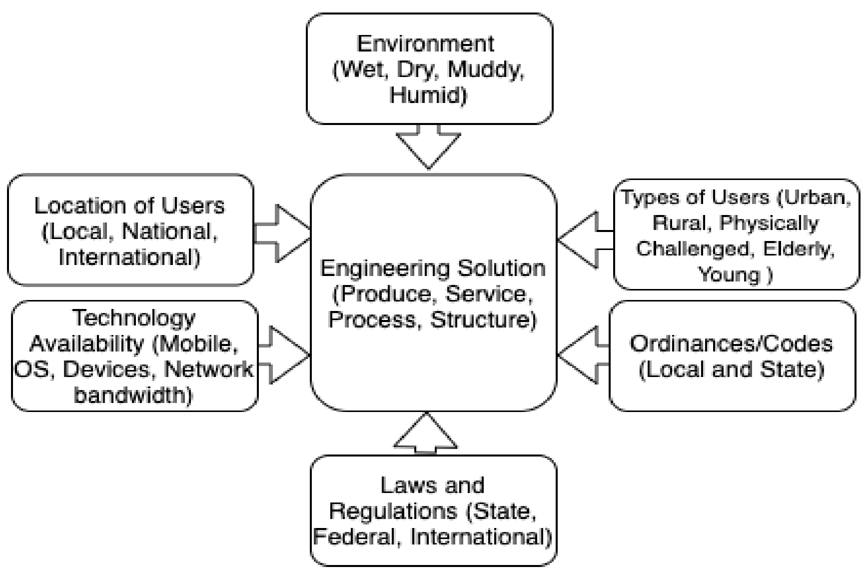

Fig. 8. The engineering solution context [13].

2.9 Decomposition

Decomposition is not the inverse of composition [29]. Tuncer et al. [29] published an overview of decomposition techniques for complex systems. They defined decomposition as breaking down a system into constituent elements. In real-life, decomposition plays a significant role in obtaining the best representation of a given system that is complex and unmanageable. The decomposition term has different meanings based on the domains in which it is being used. For instance, decomposition means factorization in mathematical analysis. In systems science, decomposition aims to find the optimal partitioning [29].

In general, the complex system is a multidisciplinary domain [49]. There are two popular ways to nearly decompose a complex system: the algorithm way or the object way [59]. Both are important, hence, it is difficult to choose which way is the best.

Several methods evaluate the optimal decomposition, such as a dispersion measure of observables, network structure, or an entropic measure [29]. As mentioned in [59], there are two categories of decomposition. [29] also illustrated these two categories. The first category is a structural method, representing the real-world phenomenon using a formal structural model. The second category is not structural; it uses the information-theoretical method without considering structure. Table II illustrates some of the well-known techniques used in these two categories.

TABLE II

DECOMPOSITION CATEGORIES [29]

The 1st category (structural)	The 2nd category (information-theoretical method)
Principal Component Analysis (PCA)	**Information Transfer Function (ITF)**

Singular Value Decomposition (SVD)	
Independent Component Analysis (ICA)	
Network Component Analysis (NCA)	

Tuncer et al. [29] discussed the main techniques for decomposition. The entropic analysis seeks the minimum entropy, making the normal distributions inappropriate. The PCA and the SVD fundamentally work with non-spherical contour distributions. According to Tuncer et al. [29], PCA is recognized as a spectral decomposition of nonsingular symmetrical square matrices and the underlying mathematical application attributed to [66, 67]. Sometimes, PCA is introduced as the Hoteling or Karhunen-Loève transform (KLT) [29, 68]. The KLT converts a set of correlated variables into linearly uncorrelated variables by utilizing an orthogonal transformation [68]. KLT is designed to illustrate the information and noise variances. Noise is linked to low variance, while information is linked to high variance [68].

SVD shows complex matrix attributes by decomposing the original matrix into many element matrices. SVD is a broadly applied technique to define the rank of the matrix, the sensitivity of a linear system, and the matrix's lower rank [69]. According to Tuncer et al. [29], the SVD technique is based on linear algebra and differential geometry that go back to the 19th century [70, 71]. In general, SVD is comparable to the spectral decomposition of square matrices [29].

In contrast, ICA is known as blind source separation [29]. The term "blind" is used because of the limitation of the source information. ICA is popular in signal processing, blind source separation, and the neural network analysis domains [72, 29]. The "Cocktail

Party Problem" is the famous problem associated with ICA. ICA solved this problem by transforming a set of transmitters into an independent set [73]. ICA works with non-normal distributions [29]. The central role of developing ICA is finding the linear description of non-Gaussian data [72].

According to Tuncer et al. [29], NCA is fundamentally similar to PCA, SVD, and ICA. All of them have a structural and a parametric method, which means they all have the same limitations. Conversely, the ITF is considered to be an information-theoretical decomposition. The ITF method does not define a structural model for the analysis process, which means it differs from PCA, SVD, ICA, and NCA. Therefore, the ITF is considered the earliest and least explored approach [29].

2.10 Summary

Complexity is a key phrase to understanding and solving today's problems. Solving a complex problem using a non-complex technique is not effective. Understanding the complex domain is a challenging task. This chapter illustrates the main fields in the complex domain to provide a deeper understanding. The science of complex systems is an interdisciplinary study that has emerged from multidisciplinary studies, such as computer science, engineering, physics, mathematics, biology, and economics [10], and appeared in the early 1970s [28, 14]. Tuncer et al. [29] have described complexity in systems as a lack of information about a system and unmanageable size, which requires high dimensionality. This shows how important information theory is in the complex domain because of the techniques that it provides for managing the information [1].

The importance of seeking the shared denominators of complex systems is a significant aspect of understanding complex systems [10]. Academia and industry began focusing on complexity science in the 1970s and 1980s. Since then, complexity science has become of significant interest to multidisciplinary areas and various theories have appeared, such as information theory, dynamical systems theory, systems theory, complex systems theory, computational complexity theory, graph theory, game theory, and social systems theory [14].

These theories describe the emergence of complexity as a result of the incremental measurement of particle disorder [44], which is recognized as an entropy [45]. The main reasons for the appearances of these theories are for studying and solving complex problems. Scholars consider uncertainty and interdependence to be essential properties of complex problems [48]. Stacey’s spectrum and the Cynefin framework address the range of the problem and help to determine whether the problem is complex or not. Therefore, complexity is associated with information, which helps to measure the complexity [29]. All the sections in this chapter explain the essential aspects of complexity to help understand the smart city as a complex system and other complex systems.

CHAPTER 3

MODELING

3.1 Introduction

Several fields are considered to be multidisciplinary, and system modeling constitutes one such field [15]. For example, scientists create system models to describe phenomena [74], and graphically representing a system is popular [75]. This chapter covers the facets of modeling, including background, system modeling, model taxonomy, model properties, mathematical modeling, information theory, system modeling and analysis using LAP, the Conant method, value-based modeling, and PArchitect.

3.2 Background

In science and engineering, modeling plays a significant role in producing rational descriptions of systems and processes. A system is a set of things working together to reach a specific goal [1]. In the engineering domain, a process is an action that works as a piece of a problem's solution. Generally, a process describes the evolutionary sequence of activities [76]. Nino [49] defined the model as “a simplified mathematical representation of a system.” Understanding the connections, theories, and principles for processes and systems plays an important role in scientifically understanding the world [76].

Frigg and Hartmann [77] cited several significant models, such as interactive models from various sciences such as cosmology, global climate models, the double-helix model of DNA, mathematical modeling in ecology and evolution, social and economic networks models, and neural network models, which illustrate the importance of modeling to science. Models differ from simulations and emulations. Models should include as few details as possible, while simulations and emulations should include as much detail as possible [49].

One of the primary role of models is to explore theory [78], which makes the modeling process a primary extension of the scientific method [74]. There are different ways to explore a theory. Some theories are too complicated to manage. For example, quantum chromodynamics is a relevant fundamental theory for the physics of an atomic nucleus, but we cannot easily use it to study this phenomenon [77, 78]. The logical model of a theory considers the accurate way to explore a theory [77]. Frigg and Hartmann [77] defined the logical model as “a set of objects and properties that make a formal sentence true, and so one can see in the model how the axioms of the theory play out in a particular setting and what kinds of behavior they dictate.”

In heuristics, purpose simulations play a significant role in proposing new theories, models, and hypotheses, and when a computer runs a simulation, it is known as a computer simulation [79]. Hybinette [80] defined simulation and computer simulation as “a system that represents or emulates the behavior of another system over time; a computer simulation is one where the system doing the emulating is a computer program.” Simulations and dynamic models are close in nature to each other. To be more precise, the result of the dynamic model’s equations is the simulation.

Alharby [19] defined the simulation as “a quantitative method, which ‘executes’ the model to mimic the behavior of the system.” Several key simulation benefits include avoiding unnecessary interference with the real system, achieving a new purpose for a system, exploring various designs, studying the trade-offs, illustrating the environmental impacts on the systems, and examining the system's performance [19]. Simulation significantly impacts on scientific endeavors, especially if the systems being represented are unachievable, impractical, or extremely expensive [81].

In general, "a simulation imitates one process by another process" [82, 79]. Comparing real-world and simulation experiments shows that simulations are safer, eco-friendly, and resource- and cost-efficient. For these reasons, simulations have been used in several areas, such as software prototyping, forecasting, planning, training and education, and analysis processes [80].

Predominately, researchers use simulation and emulation interchangeably. However, there are distinct differences between simulation and emulation [83]. For instance, simulations focus on the system's modeling components. In contrast, emulation focuses on emulating the system's behavior. In other words, emulation focuses on what systems do, and simulation focuses on how systems work [84]. Similarly, however, both simulation and emulation imitate real systems in a virtual environment [83].

Hybinette [80] compared simulation and emulation. In her comparison, she considers emulation to be a particular type of simulation, as shown in Fig. 9. The emulation could be a computer or program that duplicates systems virtually. In comparison, simulations consider more abstract behavior functions [80].

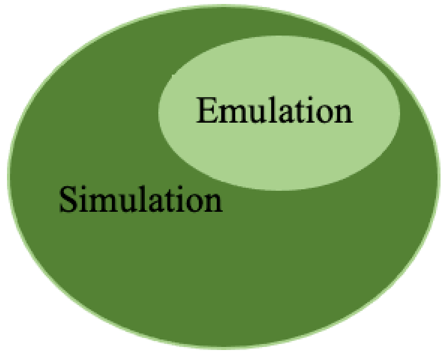

Fig. 9. Emulation versus simulation [80].

3.3 System Modeling

System modeling is a way of representing a system graphically [45]. System modeling is also “the process of developing abstract models of a system” [75]. The primary purpose of system modeling is to make rational models of a system. In other words, modeling represents a system graphically. Models play an essential role in analyzing and understanding a system’s functionality. Systems have many features, but not all the features are included in the model. Modeling focuses on the features that play a significant role in interpreting systems, problems, or observed phenomena [49]. Four perspectives exist in modeling: an external perspective, an interaction perspective, a structural perspective, and a behavioral perspective [85], as presented in Fig. 10. When the model represents the environment of the system, it is known from an external perspective. When the model represents the interactions of the system’s components or between a system and its environment, it is known from an interaction perspective. From a structural perspective, the model represents the processed data in the system. The final perspective is a behavioral perspective, which represents the dynamic behavior of the system [86, 75].

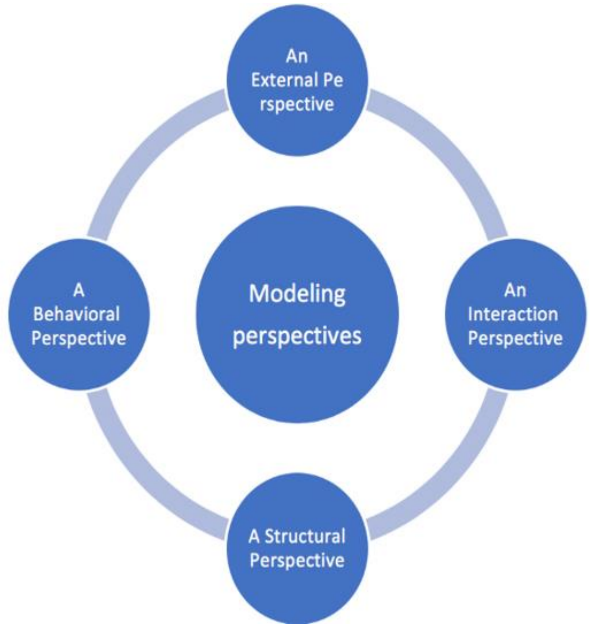

Fig. 10. The four perspectives of modeling [85].

In the engineering field, modeling is essential for both new and existing systems. In an existing system, modeling plays a significant role in clarifying the existing system’s strengths and weaknesses. Doing so will help improve the existing system and help identify the requirements for a new system. In a new system, modeling plays a significant role in explaining the system's requirements and stakeholders. The primary goal of these models is to examine a system’s design [75].

Modeling complex systems necessitates another level of modeling. The field and purpose of the study determine the model’s complexity [19]. Several modeling methods can construct models that solve engineering problems. For example, Fig. 11 illustrates a value-based engineering process that addresses complexity [13].

There are several terms important for understanding the value-based engineering process: complexity, context, convergence, and creative satisficing. First, complexity includes emergent characteristics, and transdisciplinary and other complexity principles, which the VBPMN section and complexity chapter explain in detail. Second, context plays an essential role in recognizing the context or elements of the domain of the complex system. For instance, context is considered the main modeling component in a smart city. We explain context in detail in the context section. We also consider whether it is an obstacle to a general smart city model and definition, which the smart city chapter further explains. The third important term is convergence. Convergence is an approach to problem-solving that considers multi-discipline engineering [87]. Convergence plays a significant role in empowering timely, cost-effective, and resilient solutions [13]. The final term delivers value on budgetary, time, and reliability constraints, thereby addressing creative satisficing [13].

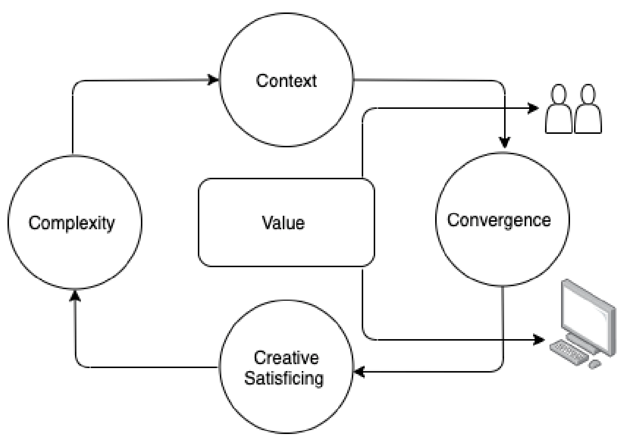

Fig. 11. Value-based process engineering [87].

In general, models that supervise a system's behavior and execution are behavioral. The main goal of these models is to illustrate the system's response in different circumstances. Several model-driven types exist: data, event, and value. First, in the data type, the model will be driven based on the data processed by the systems. Second, if the model is event-driven, the model will be driven based on certain events. Third, the value-driven modeling technique uses values as the model's primary drive. The VBPMN section explains value-driven modeling in detail.

In process modeling, there are three main critical points that play a significant role in how the stakeholders must perform in a system. The first point is stability versus flexibility. The correlation between stability and flexibility plays an essential role in managing the system successfully. The second point is modularity versus interconnectivity. This point plays a critical role in leveling the modularity of each system, which will help to maintain control over internal systems. The final point is long term versus short term. Ignoring some objectives to reach only short-term goals will lead to the long-term deterioration of the system.

Raymond and his team proposed a three-dimensional approach to the modeling process [86]. This approach helps to avoid and solve the complexity and interdependency issues, which have three main dimensions: activity, infrastructure, and communication, presented in Fig. 12, infra. The activity dimension focuses on task scheduling and performance. The infrastructure dimension works on supporting the trade-off analysis of long term versus short term. Finally, the communication dimension plays a leading role in the relationship between the stakeholders in the system. The three-dimensional approach is an effective way to develop a process model.

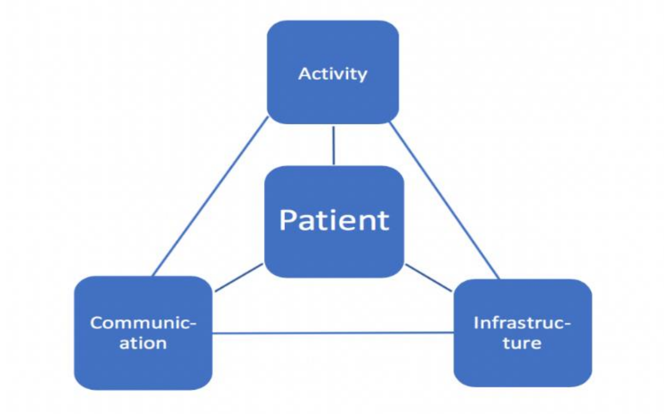

Fig. 12. The three-dimensional approach to the modeling process [86].

3.4 Taxonomy/Types of Models

The modeling domain contains different taxonomies (types of models). For example, there are several types of computer models, such as aerospace models, architecture models, astronomy models, and biology models. In addition, other computer models exist in various sectors such as behavior, cognitive, disaster, ecology, entertainment, physical sciences, robotics, transportation, and weather [88, 1].

Before the computer era, theoretical studies illustrated the scientists' path forward. For instance, numerical methods solved ordinary differential equations [89]. This section will cover the static and dynamic model classifications. Winchester [1] has discussed computer models, formalized/symbolic models, and analog models. Predefined models and iterative methods are the two computer model types in the domain of computer models. There are also formalized/symbolic models whose primary role is to create a simplified representation of the real system. In contrast, analog models use familiar systems to model the real systems [1].

Mihram [74] proposed a model classification, as illustrated in Fig. 13. Generally, Mihram classified models into two classes. The first class is static, which means models do not change perceptibly with time. The second class is dynamic. In this class, the models change over time [13]. The internal categorization of the models are divided into two types. The first type are material models, and the second type are symbolic models. A photograph and weather map are static material models. In contrast, a planetarium show is a dynamic material model. Ohm's law is a static formal model, while Lanchester's laws are a dynamic formal model. Such models aim to understand and solve societal, political, psychological, medical, judicial, environmental, social, economic, and biological problems.

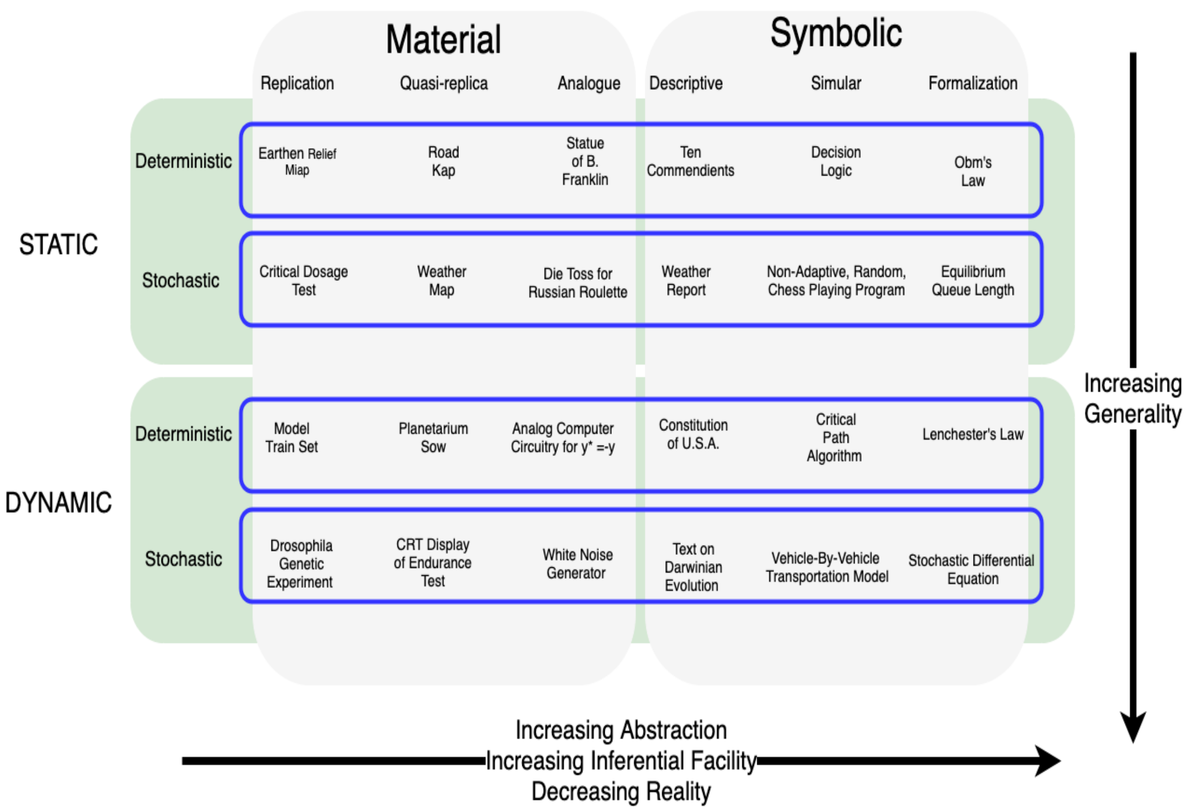

Fig. 13. Exemplary models and their classes.

As a consequence of this classification, there are two modeling process classes: material and symbolic [74]. A model is more comprehensive than being simply a combination of process steps, formulas, parameters of interest, inputs, outputs, transition points, and classifications [13]. A model can represent a single process, multiple processes, or an entire system [87]. Combining the convergence, complexity, and software engineering principles plays a significant role in creating a comprehensive view of the problem to be solved, which helps to explore the vulnerability and risks associated with the problem [13].

3.5 Model Properties

In the modeling domain, modeling properties struggle against each other, which makes modeling a challenging task. Mihram [74] represented the relationship between modeling properties regardless of upgradability, which Table III illustrates. Modelers consider upgradability to be an independent model property [1]. In general, accuracy, speed, simplicity, descriptive, openness to upgradability and maintainability, and abstraction are the main properties of models [1].

TABLE III

METHODOLOGY FOR MODEL ANALYSES

Analytical Goal	Model Category	
	Deterministic	Stochastic
1. Dynamic Effects	Fourier analysis Polynomial curve fitting	Tintner's technique Auto correlogram Spectral analysis
2. Marginal Effects	Discounted Cost-Effectiveness Comparisons	Factorial Experimental Designs Regression Analysis Multiple Rank Tests
3. Optimal Conditions	Optimum-seeking methods	Response Surface Methodology Stochastic Approximation

As previously mentioned, good models consist of several properties. Winchester [1] discussed these properties to answer the question of what makes a good model. Beginning with accuracy, this property is all about resource trade-off [1]. Roman et al. [90] defined accuracy as a parameter that compares the model's performance to the actual value, which can be performed using verification and validation processes. In general, the verification process ensures the accuracy of a model's implementation [19]. This shows the importance of resources, given that more resources positively affect the model's accuracy. The consumption of time, energy, and cost are significant factors in measuring the model's accuracy. Roman et al. [90] proposed calculating the model's accuracy by dividing the right prediction observation by the entire observation. Moreover, we can use test data in a new model [1].

Speed is considered an essential property of a good model. Winchester [1] presented two examples to illustrate the role of speed in good models. First, the circuits are more understandable and efficient because of the symbolic representations. Second, computers spend considerable time simulating molecular dynamics. As mentioned, properties struggle against each other. For example, the number of details (descriptive), agents (openness), and calculations (accuracy) play a significant role in the model's simulation speed.

Simplicity and descriptiveness are key challenges because the model needs to be simple and describe the system's properties. In the complexity domain, several parameters and connections make simplifying a model a challenging task [1]. Scholars prefer simple models over complex models for three main reasons: to prevent overfitting and for interpretability and computational efficiency [91].

Gloag [92] defined abstraction as "a process of simplification." The abstract models are less analytic because they have fewer parameters [8], making them both more general and simple, hence, consuming less time and energy. However, the model should satisfy the validation step. The primary role of validation is to represent the real system precisely [19]. The model must adapt to new scenarios, design, details, and results. Models in the complex domain must be upgradable due to the emergence of complexity. A model should also manage feedback to achieve the right upgrade and high-level maintenance, and modelers consider this function to be a significant challenge in the complex domain. Scientists consider a complex system model to be a good model if it is general, abstract, and upgradable.

3.6 Mathematical Modeling

Scientists develop mathematical representations of a system (models) to describe the time evolution of a system [49]. Mathematical modeling is recognized as the universal method for increasing modeling improvements. Consequently, mathematical modeling is the most popular modeling technique [45]. Mathematical definitions and relations are applied to the reformulation of a system. For example, the first mathematical definitions of information were proposed by Shannon [32]. In addition, in his paper "A Mathematical Theory of Communication," he designed a theoretical information model, which we further explain in the information theory section.

There are three main categories for mathematical modeling [93]: concrete, abstract, and mimetic. The first category, concrete, represents physical scale models, of which a model airplane is one example. The second category, the abstract model, consists of a numerical approximation. The third category, the mimetic model, represents a virtual reality (VR) environment.

To construct a model, the modeler progresses through five stages. The first stage is system analysis. The purpose of this stage is to understand the system interactions, which helps to understand the real-world system. The second stage is system synthesis. The purpose of the system synthesis stage is to define the steps of the model. The third stage is verification. The purpose of this stage is to develop a model. The fourth stage is validation. The purpose of the validation stage is to test the model. Finally, the fifth stage is inference, the purpose of which is to evaluate the results.

Fig. 14 depicts a flow graph of the general steps of mathematical modeling. The modeling goals and motivation are the main first steps in the modeling process before the modeling process even begins. Our mathematical modeling process begins with understanding the real-world systems by analyzing the system's interactions and then developing the model and the information flow for the system. To reach this stage, data analytics take place. The main goal of analyzing the system's information flow is to ascertain the model's initial results. We interpret these results with the real-world system. The interpretation stage has two outputs. First, the model development circle is completed if the model reaches the validation criteria. If not, adjustment is required. In that case, the model development process returns to the system's information flow stage until the model meets the validation criteria.

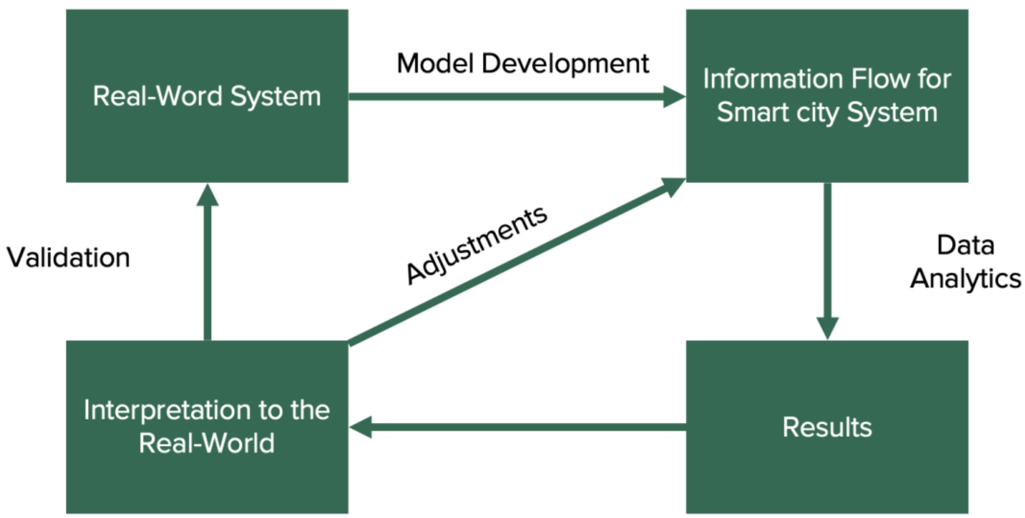

Fig. 14. The modeling process [1].

Finally, Mihram [74] presented the construction of the modeling process. The modeling process is similar to the scientific method and consists of system analysis, validation, synthesis, and verification. In a model's development, the system components are decomposed in the system analysis stage to construct a model in the system synthesis stage. Next, system synthesis is checked in the verification stage by comparing the model's responses with the expected responses. Next, the system analysis checks the validation stage by comparing responses from the model to find any differences to the actual system.

Finally, the experiments are directed in the reference stage (model analysis) with a verified and validated model. In this stage, the methodology for achieving particular modeling goals depends on the model's environment [74].

3.7 Information Theory

Information theory addresses the different states of the processing and transformation of information [45]. There are several challenges in information theory, but information storage is the important one [94]. In addition, information theory plays a significant role in transferring information [15]. Communication theory focuses on information transformation problems, and Dr. Shannon is the most well-known contributor to this field [95]. Dr. Shannon supplied the mathematical definitions of information [32] and a theoretical information model. Dr. Shannon created information theory to solve engineering problems, of which messages transferred over a noisy communication channel was the main one. Fig. 15 illustrates Dr. Shannon's general communication system.

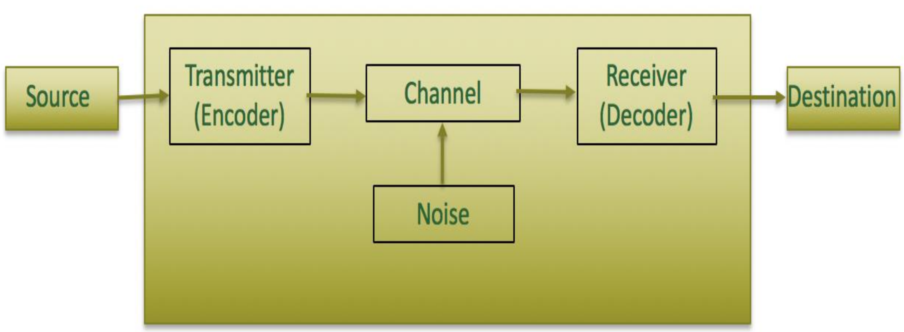

Fig. 15. A diagram of a general communication system [32].

Information theory is a technique that is used to manage information. Claude E. Shannon was the first one who developed it [96]. There are several applications for information theory in different fields, such as natural language processing, cryptography, and coding theory [45].

Entropy is “a measurement of the disorder of particles” [1]. Information theory uses entropy to illustrate information disorder [32, 1]. In entropy, the disorder of the particles in thermodynamics is similar to that of the information in communication theory, which formulates the phenomenon’s definition, mathematical tools, and theory [1]. By studying information entropy, we realize the universal goal of information theory. For example, the receiver will be able to understand the message even if the message has a missing signal. This shows how information theory plays a significant role in digital technologies.

3.8 System Modeling and Analysis Using LAP

What makes the mathematical definition of a model exceptional is its modification ability. In addition, visual representations such as graphic descriptions, plots, images, and drawings make models, solutions, or problems more understandable. In contrast, terminology and syntax are considered a challenge because every discipline has its own technoscientific language [1, 45]. Furthermore, researchers visualize systems to predict their behavior and observe what occurs when systems face different circumstances. Consequently, researchers broadly use visualization in several domains.

In this dissertation, we use a maximum independent set (MIS) to find the LAP. After converting the system into a graph, we can apply MIS and then identify the LAP, as shown in Fig. 16. The process of converting a system into a graph is difficult. The conversion process requires an in-depth analysis and understanding of the system. The MIS describes the problem visually, which makes the problem easier to understand. After applying the MIS, the LAP is attainable. We explain the LAP and MIS in the following paragraphs.

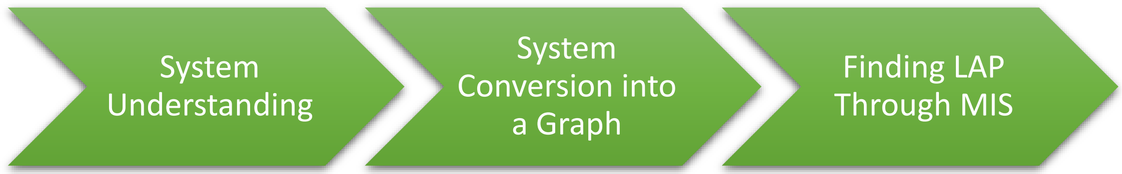

Fig. 16. Modeling and analysis of a system using LAP [1].

Guldal [45] proposed using the LAP in information theory to model and analyze systems. In addition, [1] used the LAP to model and analyze Internet of Things (IoT) systems. In classical mechanics, the LAP is broadly applied to solve problems [97, 1, 45]. Assuming all systems prefer the shortest paths, based on classical physics, the shortest path consumes the smallest amount of energy and time, which makes energy a resource. If the system requires fewer resources than the shortest path, that action will be the least action [1]. In general, LAP claims that if the action does not affect the system, it is known as the least action, and if a particle wants to move from point A to point B, it will seek the path that requires the least energy consumption [45]. To comprehend Dr. Guldal's technique, we need to understand the MIS.

The MIS is well-developed in graph theory [45]. To understand the MIS, a set, an independent set, the MIS, and the maximum independence number of a graph first need to be defined. These definitions are based on the graph theory perspective:

- A set is a collection of graph vertices
- An independent set is a set of vertices in a graph that are non-adjacent
- The MIS is a subset of independent sets and the largest set of independent sets
- The MIS size is defined as $\alpha(G)$, the maximum independence number of a graph G.

If we make a graph that has eight vertices, these vertices are connected randomly. There are independent sets with one, two, or three elements in the graph. These are some of the independent sets:

- Independent set with one element {A} and {B}.
- Independent set with two elements {A, B} and {A, E}.
- Independent set with three elements {C, E, F}.
- Independent set with four elements {C, A, H, G}.

The maximum independence number, $\alpha(G)$, is 4. Therefore, an independent set with five elements is impossible for this graph.

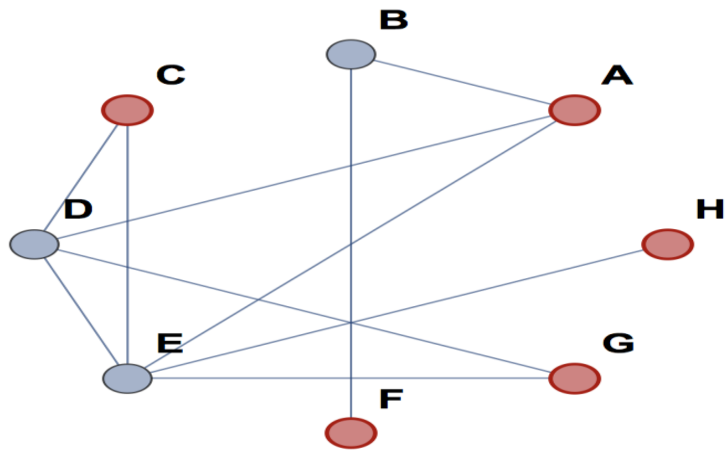

Fig. 17. The MIS.

3.9 Conant Analysis

According to Roger Conant in his paper, “Detecting Subsystems of a Complex System,” there is a way to identify potential hierarchical subsystems. He proposed user groups of variables to calculate transmission parameters [25]. His proposed method plays a significant role in understanding variable interactions in a complex system by measuring the intensity of the pairwise interaction, which makes more sense of the data collected from the system’s variables. Additionally, researchers have examined Conant’s analysis in several dynamic systems [98, 99, 45]. Conant plays a significant role in nearly decomposing complex systems, as explained in Section 2.9 in Chapter 2. The Conant method lowers the complexity of complex systems by nearly decomposing the complex systems. Doing so helps the observer to easily understand the system and find more information to scrutinize. Conant uses an entropy approach [29].

The entropy of several observations of the variables builds the transmission parameters. Grouping the joint entropy of the variables is also used. To make the observation process clearer, let us assume there are five variables. The first observation is 1, 2, 3, 1, 3. The second observation is 1, 3, 2, 3, 2. Therefore, the first observation of the set {X1,X'1} is 11. Based on this observation, the set {X1,X'1, X2,X'2, X3,X'3, X4,X'4, X5,X'5} is 1123321332. In general, a series of the observed values of the individual variables constructs the observations of sets of variables. The case study offers further explanations of this method.

The groupings are considered satisfactory if the transmission within a sub-group of variables is more significant than the transmission between sub-groups. A significant number of observations are required to obtain rationally accurate entropy estimates. The estimated number of occurrences of each possible state of the variable is known as entropy. When we obtain that number, we can apply the following equation (3.1):

$$H(S_i) = log_2(N_i) - \sum_{j=1}^{m} \frac{n_j}{N_i} log_2(n_j) \quad (3.1)$$

A set of variables = S_i
The number of observations for the set = N_i
The number of possible states for the set = m
The number of occurrences of each state of the set = n_j

Conant includes several steps in the calculation. The calculation begins with the transmission between two sets of variables, calculated by the (3.2) equation. The representation of the transmission from a set i to set j is T (S_i : S_j). On the other side, equation (3.3) calculates the transmission between multiple variables. Additionally, the equation calculates the transmission within a set j (3.4). Finally, the (3.5) equation calculates the set. All the equations are presented infra. The case study calculations clarify all these equations.

$$T(S_i : S_j) = H(S_i) + H(S_j) - H(S_i, S_j) \qquad (3.2)$$

$$T(S_1 : S_2 : \cdots : S_m) = \sum_{i=1}^{m} H(S_i) - H(S_1, S_2, \cdots, S_m) \qquad (3.3)$$

$$S_j = \{X_{j1}, X_{j2}, \cdots, X_{jn_j}\} \qquad (3.4)$$

$$T_{wj} = T(X_{j1} : X_{j1}' : X_{j2} : X_{j2}' : \cdots : X_{jn_j} : X_{jn_j}') \qquad (3.5)$$

3.10 Value-Based Business Process Management Network Model

Cherni et al. [100] defined business process management (BPM) as “a discipline in which people use various methods to discover, model, analyze, measure, improve, optimize, and automate business processes along their lifecycle.” BPM plays a significant role in solving current challenges such as complexity and competitive business environments, which are ideal for business process improvement [101]. Value-based modeling is a business modeling technique [101, 102]. A complete or partial system implementation of the model is possible in the model-driven engineering process [75]. Usually, value-based models are popular in the commercial service development domain. Representing the ways of exchanging economic values and service outcomes between actors with a focus on offering, accepting, and exchanging value in the network is the primary role of value-based modeling. Furthermore, value-based models describe the values of transaction results [102].

Mihram [74] cited many advantages for process-oriented systems engineering. For example, it is easier to understand the roles and responsibilities of the components without the need to understand the system. It also provides a way to manage a project; reducing dependencies between programs that are being developed by different working groups' components. Furthermore, process-oriented systems engineering provides a unified understanding of design patterns, code functions, necessary skills, and changes. The changes have a multiplying effect because of the hidden input and output between the levels of the system.

Sobrinho et al. [54] originally proposed the VBPMN. This modeling methodology solves the shortage in the modeling domain. Managing complexity from a software engineering perspective is difficult. This modeling technique proposes combining complex theory and software engineering principles to find the minimum requirements to design complex process technology [54].

Determining a complex process's axiomatic, algebraic, and transitional properties is essential. These specifications analyze the architecture of complexity in complex processes. Unfortunately, there is a shortage in the modeling of complex processes; the VBPMN solves this shortage [54]. The VBPMN is a backward modeling technique that starts from the complex process's goal. In VBPMN, several criteria and mechanisms guide the model and co-evolution components and are elementary in complex processes, such as "measures of alignment and efficacy," work effort for changes, productivity, synchronicity, parallelism, inclusion, and traceability. We list and explain these and additional criteria as complex systems principles, illustrated in Fig. 18.

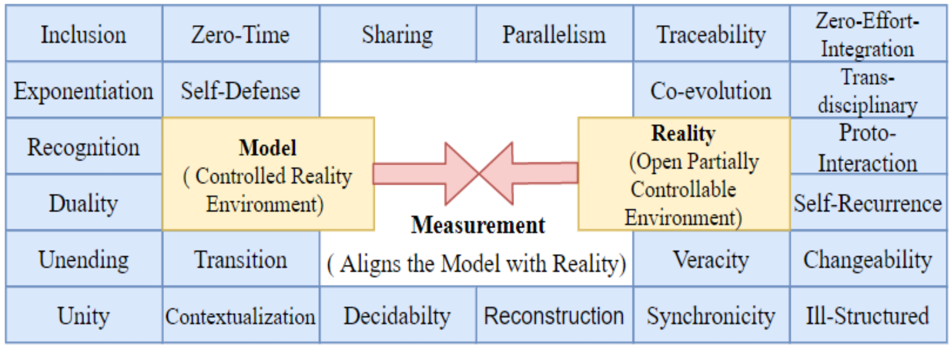

Fig. 18. Principles of complex systems in VBPMN [54].

These principles of complex systems in BPM network engineering are advanced. Beginning with inclusion, value inclusion has been developed in the complex domain. For example, the same value can have two distinctive conflicting contexts, but both contexts are considered in the same process. These contexts will be defined based on the complex process environment and may be engineering, social, economic, scientific, technological, or educational contexts. The exponentiation principle focuses on the position of decision-making. The value will be different in each modeling stage, and exponentially traced by environmental, technological, or human resource references at the same time.

Recognition addresses how to recognize the value in the process. Values affect each other by nature or validity and synchronism. These effects are recognized as values (initial, intermediate, and final), references, and infrastructures based on the context. All these recognitions explain the complex process behavior within a context. Duality presents a challenge in modeling complex systems because duality increases the complex level of Value A, which leads to managing more complexity. It allows the primal problem different dualities, or each duality allows different primal problems. The value's duality represents the characteristic of a value, stated as "Duality of a Value A is not necessarily the Value A" [54].

The unending principle indicates that some processes do not end, and the results are different each time. The unending process may be an input for another process, which makes modeling complex systems more difficult. Unity is also a challenge in modeling complex systems. In general, it is a way of describing the process. If the unity is not known, then neither is the process. Unity is not a set. For example, unity can be a student, class, or community. Timing also plays a significant role in the modeling domain. Overall, there are three timing approaches: negative, positive, and zero time. In negative time, the model generates the value after it is needed. In positive time, the model generates the value before it is needed. In zero time, the model generates the value is generated when it is needed.

Contextualization also has a significant impact on complex modeling systems. For instance, there is no general smart city model because each smart city model has its own context [7]. A value can be confusing; understanding the concept or the context is therefore essential. Furthermore, the exact value may have different contexts throughout the process. For example, the roles of the same value may be that of a student, teacher, or worker depending on the context. "A value may be differentiated as a reference, an infrastructure and as an input in the same decision in three different contexts, which integrate into one context" [54].

The value must have all the requirements and references it needs to defend itself. Sometimes a value may not occur with the presence of other self-defense values. "In other words, a disease may not occur if the organism has the required immunology." The value may not exist when we have procedures occurring in real-time to cope with social disasters or some of the values that would only occur because of a lack of self-defense. Proto-interaction reduces the differences in VR and practices to obtain value. In addition, the value can be recurring, and it may be unending. The only way to know whether the value will stop is if it does not change or requires different characteristics with its generation, known as self-recurrence.

Sobrinho et al. [54] also discussed synchronicity, parallelism, veracity, co-evolution, traceability, ill structure, changeability, and reconstruction. Synchronicity is required to generate new values, which represents the context validity for all values simultaneously. Parallelism means exploring any transitions for any values without considering the dependency, sequencing, interactions, and synchronicity between them. Veracity means constantly measuring the differences between the value's abstraction and reality. The value's characteristics play a vital role in reducing the differences between abstraction and reality, which represents co-evolution. Traceability works through visualizing the dependencies of a value, which include values or legacies, and any other influences at the same time. To avoid the ill-structured principle, the value is responsible for generating the structure and not the inverse. In addition, the value may have different structures in the same context. Changeability means the value can continuously change independent of time and space. Reconstruction allows the use of the values, synchronisms, transitions, and contexts of a system to reconstruct different values with the same properties of the design.

3.10.1 PArchitect

P3tech PArchitect is a backward value-based driven modeling technique based on the VBPMN proposed by [54]. PArchitect is a P3tech tool used in strategic operations management, analyzing processes, and providing solutions. P3tech is a value-based process approach that stands for Process Production Process [103]. This software has several essential components: values, connectors, timer and protocols, and transitions. Table IV illustrates these components.

TABLE IV

P3TECH MODELING COMPONENTS

	TRANSITIONS: Can be simple, composite, automatic, batch, and automatic per lot.
	VALUES: Can be initial, intermediate, or final value and any kinds of references.
	INFRASTRUCTURE FEATURES: Can be human resources, technological resources, environmental resources, and resource tooling.
	CONNECTORS: Can be a flow of value (the connection between a value and a transition), reference flow (the connection between a reference value and a transition), and infrastructure association (the connection between an infrastructure resource and a transition)

Transitions are not functions, but procedures that add knowledge to the value results domain [54]. Values can be final values, initial values, intermediate values, reference values, and infrastructure values. The final value is selected first, that is, the system's primary goal. Next, initial values are added. Following this, intermediate values and added values can be included. Added values are the output of a transition or transformation, also described as action results. Reference values provide the guidelines or laws of these transitions, and the transition should obey these reference values. There are also infrastructure values, which are human resources, environments, or technologies. The model needs these values to perform.

There are two main connectors: input connectors and output connectors. There are two types of input connectors: “input-or” and “input-and.” The input-and connectors allow multiple input values to join a transition. The input-or connectors allow multiple input values to be joined, but a transition will recognize only one value. There are also two types of output connectors: “output-and” and “output-or.” The output-and connectors allow various output value flows to be joined. As a result, only one is followed. The output-or connectors allow multiple output value flows to be joined at the same synchronicity. As a result, all the flows are followed.

These two paragraphs explain two critical concepts: the timer and protocols. The timer helps to model recurring events or events required at a particular time. With regard to the protocols, there are five main types: input, output, reference, infrastructure, and timer. The input protocols work with input values. The input value is “reset” when the transition is performed, which shows that the value has been used and is ready to reuse.

Conversely, the output protocol works with output values. It acts in a similar way to the input protocol but on the output line-up. Once the reference value is established, the synchronicity is validated for the reference protocol, associating a reference value and a transition. For the infrastructure resource value, the infrastructure protocol clarifies an added value. The final protocol is a timer which is a timer to send activity inputs.

3.11 Summary

System modeling is a multidisciplinary field [15], which creates abstract rational replications of a system [75]. These models have a vital role in describing systems [74]. Modeling has commanded the attention of scientists from many fields and hence produced a number of significant models: interactive models, the double-helix model of DNA, mathematical modeling, social and economic networks models, neural network models, and others [77]. Furthermore, models play a significant role in studying theory [78], especially complex theories that are too complex. The features of these models demonstrate the importance of modeling and present them as extensions of the scientific method [74].

Models play an essential role in analyzing the functionality of a system. However, system models do not include all the system's features. A model can represent many processes or a full system [87]. Usually, models are driven by the specific features that have a significant role in describing the systems [49], with an external perspective, an interaction perspective, a structural perspective, or a behavioral perspective [85].

In modeling complex systems, researchers have evolved modeling to another level. Researchers have proposed many modeling techniques to solve engineering problems, but not all of the techniques address the issue of complexity. However, the value-based engineering process technique does consider this issue. It addresses the roles of complexity, context, convergence, and creative satisficing in solving complex problems. The fundamental arguments in process modeling are also worth mentioning: stability versus flexibility, modularity versus interconnectivity, and long term versus short term. These arguments have prompted scientists to propose methods to solve the complexity and interdependency problems, such as Raymond's three-dimensional approach [86] and the value-based engineering process method [87].

Moreover, scholars proposed mathematical modeling to describe the time evolution of a system [49], which is the most popular modeling technique [45]. Shannon [32] discussed and defined information mathematically. He also introduced a theoretical information model that addresses the different states of information (information theory) [45]. Based on Shannon's theory, Guldal proposed a modeling system using LAP [45], which uses the MIS as a tool to obtain the LAP. However, decomposition is problematic in complex systems, and scholars have proposed several ways to address this problem, as cited in the complexity chapter. Conant proposed a method to detect the subsystems of complex systems [25].

Convergence, complexity, and engineering principles play a significant role in understanding the problem. The primary purpose of creating the VBPMN was to solve the shortage in the modeling of complex systems. The VBPMN unites the complex theory and software engineering principles, which helps to minimize the requirements for complex processes [54]. Corresponding to the VBPMN, the PArchitect tool has emerged [54]. PArchitect is a strategic operations management tool that plays a significant role in analyzing processes and providing solutions. Finally, the characteristics of a good model are generality, abstraction, and upgradability [1].

CHAPTER 4

SMART CITY

4.1 Introduction

In the ICT domain, no standard definition for “smart” exists [104]. Nonetheless, the term has been used extensively. It often describes clever, modern, and intelligent ideas or objects. Therefore, “smart” is a broad term but the growth in “smartness” plays an important role in achieving high efficiency in city transportation, healthcare, education, governance, mobility, and economic development [7, 105].

From an ICT perspective, the term “smart” is complicated. Several synonyms often replace the term. Nevertheless, in the ICT domain, “smart” means being efficient and knowledgeable [6]. Arroub et al. [2] defined smart as “a means of a prospective performing taking into account the development-aware, flexible, transformable, synergistic, individual, self-decisive and strategic aspects for achieving smartness.”

According to the United Nations (2005), a city is an urban area with 1,500 people per square mile [7]. This number differs from one country to another. Megacities are cities that exceed a population of 1.5 million [7]. Another paper notes, “the city is an urban community falling under a specific administrative boundary” [106]. A group of people who have organized responsibilities, activities, and relationships is known as a community [107]. The International Standards Organization (ISO) states the general definition as [3] “a city is a system of systems with a unique history and set-in actors who need to work together, utilizing all of their resources, to overcome the challenges and grasp the opportunities that the city faces" [7]. Das et al. [6] provide a logical explanation by defining a city as "an urban community falling under a specific administrative boundary." Two city classifications also exist: new and existing [108]. Tianjin (China) and Masdar City (Abu Dhabi-UAE) are new cities, while Cyberport Hong Kong (China), Songdo International Business District (South Korea), Cyberjaya (Malaysia) are existing cities [7].

Cities have physical and social components, which means they are complex systems [5, 6]. The physical components are all physical resources and processes. The social components are people, institutions, and activities [7]. Some researchers refer to these components under different names, such as hard and soft resources [108, 109]. For example, buildings, streets, networks, and bridges are hard components and people, organizations, and knowledge are soft components [7]. Anthopoulos [7] presented a comprehensive view of the smart city, which we have used as one of the main resources for the smart city chapter. This chapter details the facets of smart cities, including definitions, and their evolution, generations, classes, dimensions, characteristics, architecture, models, requirements, challenges, and assessment.

4.2 Smart City Definitions

The term "smart city" appeared in the early 1990s [110, 7]. Since then, the term has continued to evolve. The evolution of smart cities has progressed from adopting simple technology ideas in government services to representing a wide system consisting of numerous characteristics, such as environmental, technological, innovation, and social facets [110]. Conceivably, the smart city works as an urban strategy that uses advanced ICT to improve the quality of life without harming the environment [111].

Darby [112] defined a smart city as “a vessel that contains a workforce that uses information technology to add the most economic value to the goods and services that originate in that city.” There is a standard limitation in smart city investigations, as they have only focused on technical aspects. A smart city does not only apply technologies to a city [4]. New investigations have shed light on the social aspects in smart cities. Social aspects play a significant role in the smart city domain.

Nonetheless, to date, the definition of a smart city remains imprecise; there is no universally agreed upon definition. Frequently, commentators have replaced “smart” with other terms such as “digital city,” “sustainable city,” “electronic city,” “information city,” and “wired city” [16]. Usually, the smart city definition is driven by a specific context. For example, it can be a technological, economic, social, environmental, or governance context.

The International Telecommunications Union (ITU) Telecommunication Focus Group on Smart Sustainable Cities defines the smart city as “an innovative city that uses ICTs and other means to improve quality of life, the efficiency of urban operations and services and competitiveness, while ensuring that it meets the needs of present and future generations concerning economic, social and environmental aspects” [110]. The ITU analyzed 120 definitions to arrive at this result [113].

Arroub et al. [2] conducted a comprehensive review of smart cities and their exposed problems. They listed several smart city definitions. For example, “a city can be defined as smart when investments in human and social capital and modern transport and communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance” [2, 24].

Geller [114] defined a smart city as "a city performing well in a forward-looking way in economy, people, governance, mobility, environment, and living, built on the smart combination of endowments and activities of self-decisive, independent, and aware citizens." Arroub et al. [2] defined the smart city as a system of systems bringing intelligence to systems to manage contributing technologies to produce innovative development.

Kondepudi [115] noted "a smart sustainable city (SSC) is an innovative city that uses ICTs and other means to improve quality of life, the efficiency of urban operations and services, and competitiveness, while ensuring that it meets the needs of present and future generations concerning economic, social, and environmental aspects" [4]. When a city provides smart interactive services with people using ICTs to improve their quality of life or services, it is recognized as a smart city [116].

Chourabi et al. [117] defined two levels for the smart city: internal and external levels. The internal level addresses the smart city initiatives and encompasses technology, organization, and policy. At the same time, the external level addresses internal components and encompasses public infrastructure, environment, technology, and governance [111].

Guo et al. [16] proposed two approaches to defining a smart city: technological and people-oriented. Daneva and Lazarov [4] also provided two approaches to smart city systems: hard (technologically intense) and soft (socially intense). In the technology approach, technologies such as IoT and Big Data are fully developed. These technologies can make city services, such as energy grids, water management, and mobility, smart. In the people-oriented approach, soft factors and people's roles are included. This approach is evident in several fields such as education, culture, sociotechnology, social inclusion, and cultural heritage.

Guo et al.[16] defined a smart city as "an urban environment that utilizes ICT and other related technologies to enhance performance efficiency of regular city operations (the local economy, transport, traffic management, environment, interaction with government, etc.) and the quality of services provided to urban citizens."

Dameri et al. [111] presented some of the smart city's most cited definitions. Hall [118] defined a smart city as a place with ICT infrastructures that manage, innovate, and preserve these infrastructures to increase the quality of life. Caragliu et al. [119] defined a smart city as a city that emerges as an integration between human and social capital and ICT infrastructures to increase the quality of life through the wise use of environmental resources.

The Strategic Energy Technology Information System - EU 2012 defined a smart city as "a city which can combine technologies as diverse as water recycling, advanced energy grids, and mobile communications in order to reduce environmental impact and to offer its citizens better lives" [111]. Moreover, Dameri [120] noted "a smart city is a well-defined geographical area, in which high technologies such as ICT, logistics, energy production, and so on, cooperate to create benefits for citizens in terms of well-being, inclusion, and participation, environmental quality, intelligent development; it is governed by a well-defined pool of subjects, able to state the rules and policy for the city government and development."

Höjer et al. [121] explain the relationship between the essential terms "smart," "cities," and "sustainable." A city can be sustainable but not use smart (ICT) technology, and it can be smart without being sustainable. Cities need all three aspects illustrated in Fig. 19 to be SSC.

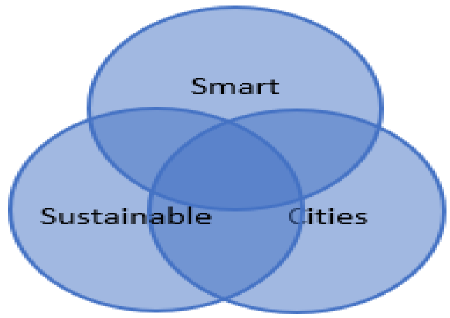

Fig. 19. Aspect of smart sustainable cities.

The European Commission programs FP7-ICT and CIP ICT-PSP [7] define the smart city as a "user-driven open innovation environment," which addresses the city as an enhanced citizen engagement platform. "Openness" plays a significant role in affecting several relationships among people, services, infrastructure, and technology [122, 7]. First, open public services provide easygoing management of people's activities. Second, open industry infrastructure and technology standards drive open-service-oriented business models [122]. Third, open innovation systems improve citizen participatory decision-making by providing high-quality social interactions [7].

Many international standardizations define the smart city—beginning with the ITU (ITU, 2014), which focuses on ICT. The ITU defines the smart city as a city that uses ICTs relating to economic, social, and environmental aspects to improve the quality of life and efficiency of services. Furthermore, ISO (ISO, 2014b) identifies a smart city as a city that uses new information technologies. In this respect, a smart city is a city that applies the

IoT, cloud computing, and Big Data to increase the quality of the design, construction, and management of smart city services.

Table V is the result of studying key publications, such as [123, 7, 124, 113, 24, 125, 112]. [123] presented smart city definitions for [126, 124, 24, 120, 127, 128, 129, 130, 131].

TABLE V

THE KEY DEFINITIONS OF A SMART CITY

Source	Definition
[112]	"In a smart city lives an information society. A smart city is the vessel that contains a workforce that uses IT to add most of the economic value to the goods and services that originate in that city. A smart city can make smart washing machines, communication satellites, or information-enriched vacations. A smart city has a physical infrastructure and regulatory environment that permit and promote the development and exchange of information with minimal transaction costs."
[126]	An "Inclusive Smart City" is a smart city that supports the access and use of urban technologies by all citizens (including people with disabilities and seniors/older adults)."
[124]	"A city performing well in a forward-looking way in economy, people, governance, mobility, environment, and living, built on the smart combination of endowments and activities of self-decisive, independent and aware citizens. A smart city generally refers to the search for and identification of intelligent solutions which allow modern cities to enhance the quality of the services provided to citizens."
[24]	"Integration of infrastructures and technology-mediated services, social learning for strengthening human infrastructure, and governance for institutional improvement and citizen engagement."
[120]	"A smart city is a well-defined geographical area, in which high technologies such as ICT, logistic, energy production, and so on, cooperate to create benefits for citizens in terms of well-being, inclusion and participation, environmental quality, intelligent development; it is governed by a well-defined pool of subjects, able to state the rules and policy for the city government and development."
[132]	The British Standards (BSI, 2014) defines a smart city as an integration of physical, digital and human systems in order to provide high quality of life for its citizens.

[127]	"A smart city is generally meant as a city capable of joining competitiveness and sustainability by integrating different dimensions of development and addressing infrastructural investments able to support economic growth as well as the quality of life of communities, a more careful management of natural resources, a greater transparency and participation in decision-making processes."
[128]	A "smart city is a sustainable and efficient city with high quality of life that aims to address urban challenges (improve mobility, optimize use of resources, improve health and safety, improve social development, support economic growth and participatory governance) by the application of ICT in its infrastructure and services, collaboration between its key stakeholders (citizens, universities, government, industry), integration of its main domains (environment, mobility, governance, community, industry, and services), and investment in social capital."
[129]	"A smart city is a system integration of technological infrastructure that relies on advanced data processing with the goals of making city governance more efficient, citizens happier, businesses more prosperous and the environment more sustainable."
[130]	[130] defines a smart city "as an integrated system of collaborative social and human capital using technological advancements to achieve a sustainable and resilient development with higher quality of life" [123].
[131]	They describe the smart city concept as "an integrated and smart method of planning, assisted by the digital infrastructure for communication and management, which would allow the city to be coordinated as a sentient, homeostatic and self-repairing organism. In other words, it could help this organism to behave as a resilient ecosystem. The regulation of the whole system through a dynamic balance is stimulated by the knowledge of the interrelations among subsystems and the real-time management of transformations."
[110]	The ITU Telecommunication Focus Group on Smart Sustainable Cities defines the smart city as "an innovative city that uses ICTs and other means to improve quality of life, efficiency of urban operations and services and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects."
[2]	"A city can be defined as smart when investments in human and social capital and modern transport and communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance."
[114]	The smart city is "a city performing well in a forward-looking way in economy, people, governance, mobility, environment, and living, built on the smart combination of endowments and activities of self-decisive, independent and aware citizens."
[4]	[115] defined a smart city as "a SSC is an innovative city that uses ICTs and other means to improve quality of life, efficiency of urban operations and services, and competitiveness, while ensuring that it meets the needs

	of present and future generations with respect to economic, social and environmental aspects.”
[16]	The smart city is “an urban environment that utilizes ICT and other related technologies to enhance the performance efficiency of regular city operations (the local economy, transport, traffic management, environment, interaction with government, etc.) and the quality of services provided to urban citizens.”
[133]	“Smart cities are the result of the use of ICTs through systems and technological tools and their application to urban projects that, based on the use of sensors, monitoring systems, wireless networks, autonomous devices, and mobile applications, collect data that serves as a source for proposing viable solutions to social problems aimed at improving the quality of life of its citizens.”
[134]	A smart city provides innovative solutions based on quality of life. This definition is not limited to innovative solutions but mainly based on the ICT that improve the quality of life in terms of people, governance, the economy, mobility, the environment and living.
[135]	[136] defines a smart city as a city that is well performing in a forward-looking way in economy, mobility, environment, citizenship, quality of life and governance, built on the “smart” combination of endowments and activities of self-decisive, independent and aware citizens.
[137]	“A city is smart when investments in (i) human and social capital, (ii) traditional infrastructure, and (iii) disruptive technologies fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance.”

In conclusion, the smart city term is typically defined based on the objective of the city. It can be based on the public services, city management, effectiveness of infrastructures, the environment, security, the economy, and society. The fundamental goal of a smart city is environmental preservation by enhancing the citizens’ quality of life [111].

Furthermore, these definitions show that smart city scholars intellectualize smart cities with alternative approaches. For this reason, Anthopoulos [7] analyzed the existing smart city conceptual models and listed eight components of smart cities: architecture, governance, planning and management, data and knowledge, facilities, services, people, and environment. The components section explains these terms.

4.3 The Smart City Evolution

At first glance, a definition of a smart city can be formed by combining the definitions of "city" and "smart"; the smart city is an urban space with smart systems. Smart systems comprise any intelligent idea, design, and process and are not limited to only ICT-based [7]. Smart cities can use all their resources to reach their goals and purposes [3]. However, as previously observed, many definitions of the term exist; hence, its meaning remains somewhat ambiguous [7].

Guo et al. [16] discovered several origins for the concept of a smart city. One of the roots derives from the 1960s and "cybernetically planned cities." In contrast, some researchers claim that smart cities have been around since the 1980s as networked cities [121]. In the 1980s, an urban development plan proposed networked cities [138]. It describes the efficient and self-governed cities in the United States [16].

In the late 1990s, the initial definitions of a smart city appeared [7]. The definitions range from ICT-based environments to transportation and smart energy consumption to the "smartness footprint" and subsequently to innovative solutions based on the quality of life [7].

The term "smart city" appeared when researchers began to define urban technology using different domains and viewpoints [7]. In the late 1990s, scholars considered installing ICT projects within the urban space. They discussed these projects with different perspectives and terms [7]. Fig. 20 illustrates the smart city evolution timeline adopted from [7].

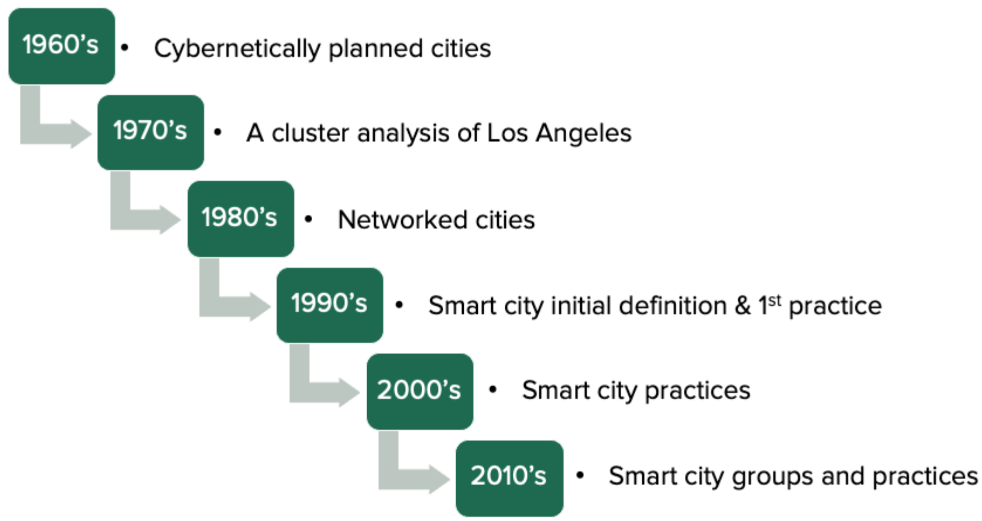

Fig. 20. The smart city evolution [7].

In 1994, the answer to the question, "can digital kiosks for travelers bring digital services to the local loop and make a city, or village, smart?" first introduced the smart city term [16, 112]. Since the 1990s, technological innovations have played a significant role in planning, developing, operating, and managing smart cities. The first implementation of a digital city was in the Netherlands in 1994 [139]. In January 1994, the De Digital Stad (DDS) was launched in Amsterdam. DDS's primary purpose was to encourage individuals to use the internet [139]. Then in 1998, Kyoto provided animations and collected citizens' communications via sensors [6]. It aimed to facilitate discourse between the community and politicians [7].

In 1997, there were over 2,000 virtual cities and urban web pages [140], and these were considered the first evidence of the appearance of smart cities. The authors describe a web or virtual city as cyber-based or virtual communities with decentralized interactive media networks [6]. The World Wide Web (WWW) played a significant role in virtual cities.

Web or virtual cities are two sides of the same coin, with the terms describing all the web activities in a city [7].

In virtual cities, the ICT digitalizes government operations to produce more socialized citizens through the creation of virtual spaces. In virtual cities, the city websites have a primary role in providing smart services, and these smart services result from cooperation between the internet, the city system, and the WWW [6]. In the 1990s and early 2000s, web or virtual cities provided public information such as about cultural events. They also provided information for public authorities [7]. In addition, web or virtual cities applied internet technology to provide e-municipal services, urban marketing, and social and community services, but the citizens' role was absent [7].

In addition, Graham and Aurigi also introduced the "digital city" term in their review [140]. The digital city is more inclusive than the web or virtual cities. It represents a discourse-driven virtual city [7]. Citizen interactions played an essential role in the beginning phases of digital cities.

In 1998, Besselaar and Beckers defined the digital city as "a large infrastructure for virtual communities" [7]. According to this definition, a digital city is more than a community network. Non-community members can register for digital city services. Based on the definitions of virtual and digital cities, they possess the same challenges, services, and technological tools. Virtual and digital cities generally apply ICT to create virtual and digital communities known as e-communities. They focus on democratizing local governments and resolving the lack of public space by providing virtual places.

City websites combined the internet, urban network infrastructure, and the WWW [7]. As a result of this combination, the city websites provided alternative smart services for their communities. The initial smart city was comprised of two approaches: a community of communities or 3D virtual spaces [7]. In 1997, Amsterdam Digital City developed into a $500,000 nonprofit organization led by the municipality and had 25 employees [7].

The digital city used ICT to innovate online services, known as information cities [122, 7]. Digital or information cities have become more prevalent in cities with embedded streets and facility infrastructures [141, 7]. The innovative online services mean the digital city and the information city correspond [6].

A new version of the digital or information city has been introduced as the “ubiquitous city” [122]. The South Korean government introduced the ubiquitous city as “a city that is managed by the network and provides ... citizens with services and contents via the network ... with a BUCI (fixed u-city infrastructure) and MUCI (mobile u-city infrastructure), built on high-end technologies such as sensors” [122]. Fig. 21 illustrates the evolution of smart cities over the decades.

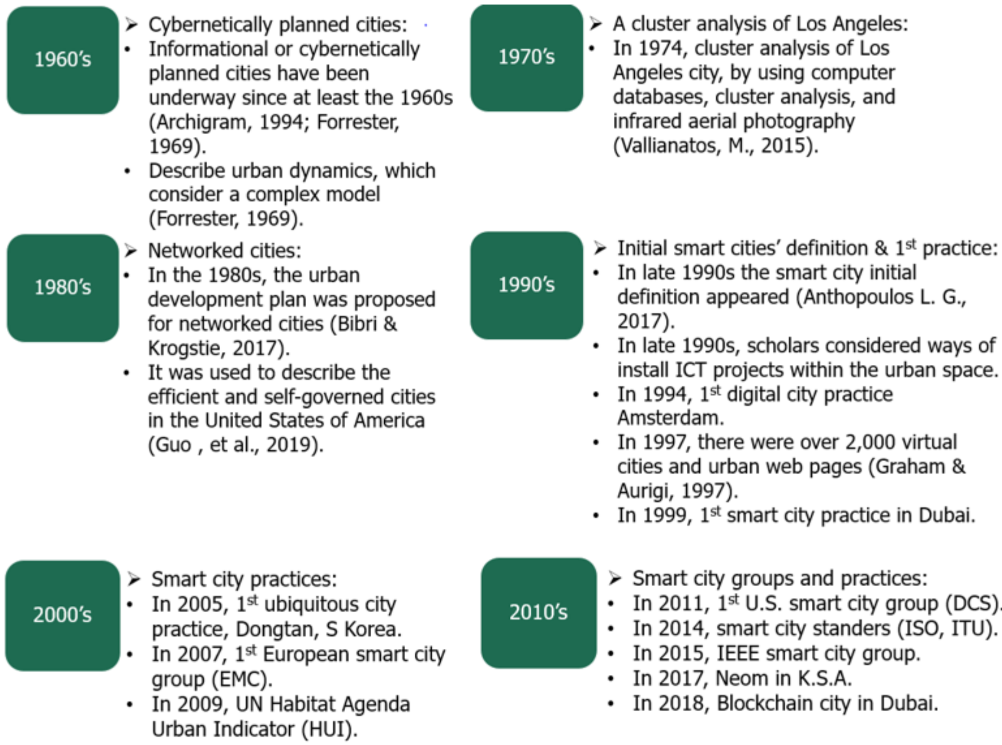

Fig. 21. The evolution of smart cities over the decades.

In addition, scholars introduced and discussed "the intelligent city." The intelligent city has three dimensions of intelligence: inventiveness and creativity, collective intelligence, and AI [122, 7]. These dimensions play a role in creating innovations that increase city performance [122]. The city performance is the primary goal of the intelligent city. The city performance depends on three main areas: original and creative intelligence, collective intelligence, and AI [6].

All these smart city types have different levels of technological embeddedness. According to [142], a smart city has four key levels of technological embeddedness. The levels begin with a low level, which is considered simple information delivery. Next is the functionality level, which involves intelligent system implementation. Then, the quality of life level, which deals with social and human interests. Finally, these lead to a sustainability level [142].

Smart cities in the ecosystem domain are relatively different. Generally, ecosystems are defined as complex networks of interacting interdependent communities [7, 143]. Maheshwari and Janssen (2014) defined an ecosystem as "an interdependent social system of actors, organizations, material infrastructures, and symbolic resources" [7, 144]. Based on these definitions, ecosystems are similar to any other type of system. However, ecosystems have characteristics that differentiate them from other kinds of systems because ecosystem qualities are smart, autonomous, interdependent, and adaptive. The four critical elements of ecosystems are interaction, balance, shared goals, and self-organization [7, 143].

4.4 Generations of Smart Cities

There are three main generations of smart city development [145], as proposed by [146]. In the first generation of smart city development, technology was the core aspect. Citizens only received services due to the lack of a digitally educated and participatory audience. The first generation provided technology solutions to citizens who did not understand the impact of these technologies on their quality of life. The second generation of smart city development used technology as the core enabler. City administrations used technology solutions as enablers to reach this generation's primary goal: improving the citizens' quality of life. Recently, a new generation of smart city development has emerged, which differs from the tech-driven provider approach (1st generation) and the city-driven or technology-enabled model (2nd generation). This generation are described as citizen co-creation models (3rd generation). The third generation of smart city development uses the bottom-up approach to motivate citizens and innovators to engage. Fig. 22 illustrates the three generations.

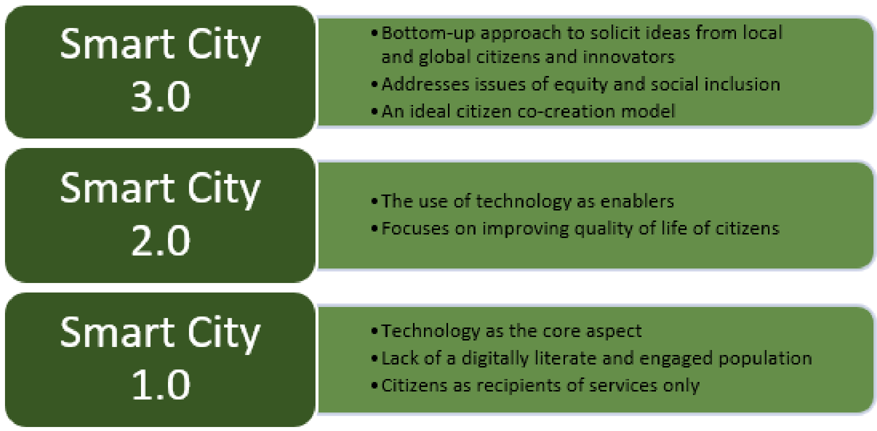

Fig. 22. The framework of the three generations of smart city development [146].

4.5 Smart City Classifications

4.5.1 Smart Cities Based on Area and System

In general, the smart city divides into classes based on measurements of population and density, impact, and development stage. In terms of population and density, there are villages, communities, towns, cities, and megacities. On the impact side, there are local and global impact cities. Finally, new and existing cities are developing [7].

Smart cities have been developing for the last 25 years. Based on that period of time, there are a number of smart city types. ICT is crucial in smart city systems (SCSs) [4]. The main goal of applying ICT is to find innovative solutions for citizens' living problems. Harrison et al. [147] proposed instrumented, interconnected, and intelligent systems as the main types of SCSs [4]. Their classification has played a significant role in creating a wide understanding of smart cities [4].

4.5.2 Smart Cities Based on Stakeholder Vision and Objectives

Alcatel-Lucent (2012) classifies smart cities into large and small smart city projects concerning "box" types of organizations and business models [7]. There are four "box" types, which are the information technology box (private partnership), the dream box (public-private partnership), the fragmented box (stakeholders), and the black box (governments or companies). [148] classified smart cities based on the vision of the stakeholders. Table VI illustrates the classification.

TABLE VI

THE STAKEHOLDER VISION AND OBJECTIVES CLASSIFICATION [148]

Category	Explanation
IT box	This smart city category, led as the IT companies with focus on IT excellent.
Dream box	This smart city category described as a turnkey smart city. This category makes a wide range plan which consider as the first step of the project and take into consideration the private and public partnership.
Fragmented box	This smart city category covers independently diverse aspects of smart cities.
Black box	This smart city category lead and manage by government administrations. It works as a closed ecosystem. Even the invited companies are government-affiliated companies.

4.5.3 Smart Cities Based on City Learning (Agencies and Networks)

Campbell [149] classified the smart city into four learning classes, namely "individually proactive city, city cluster, the one-to-one link between cities, and city network" [2]. Observing the processes (creation, storage, and conversion knowledge) in city learning simplifies categorizing city-to-city exchanges in terms of the effort exerted, learning objectives, and interaction modes between the cities' actors. [149] described the proactive city as a city that "takes the initiative in the outward search for knowledge and information; commits resources to incorporating knowledge in policy and practice." Seattle is one of the examples in this class. Learning in this class is based on proactive stances. Class two is a city cluster, which means the learning process is based on clustering self-defined cities as class members. Sustainable cities, port cities, and Olympic cities are considered to be examples of this class. This class works consistently and relatively and has limited focus compared to the first class (a proactive city). The third class is described as individual cities, one-to-one, or communities within cities. In this class, transferring technical skills between cities is intermittent. Usually, the exchange agreement is for a short duration. VNG in the Netherlands is an example of the third class. The fourth class is the city network. In this class, cities are members of organizations or associations that lead the learning process. The Local Government Information Network is an example. Table VII illustrates the typology of the city learning agencies and networks classification [149].

TABLE VII

THE LEARNING AGENCIES AND NETWORKS CLASSIFICATION [149]

Grouping	Example	Characteristics of learning
Proactive cities	Bilbao, Curitiba, Seattle	Takes initiative in outward search for knowledge and information; commits resources to incorporating knowledge in policy and practice.
City clusters	UNESCO World Heritage Cities; Bertlesmann Cities of Change; ICLEI Agenda 21	City members of a class involved in more or less sustained, but episodic programs of exchange; intermittent technical meetings and visits.
Cities one-on-one	ICMA City Links; Federation of Canadian Municipalities; Sister Cities,	Agreements between cities for periodic one-on-one exchanges of short duration.
Networks	UCLG, Infocity, AsiaCities CityNet, VNG in the Netherlands	Membership organizations with convening power (e.g. UN) working on behalf of members on technical, regulatory, or legal matters.

4.5.4 Smart Cities Based on Technology

Furthermore, Anthopoulos and Fitsilis analyzed the role of ICT in 34 different smart cities [7]. They discovered ICT alternatives embedded within smart cities. Eight categories emerged as a result of this analysis: the web or virtual city, the knowledge city, the broadband city, the mobile/wireless city, the digital or information city, the ubiquitous city, the smart city, and the eco-city [7, 141].

In general, the web or virtual city consisted of virtual meeting rooms such as online chatting. Examples are Kyoto, Japan (1996–2001) and Amsterdam (1997). The knowledge city is a digital public city that users can reach using the internet or television. There are several examples of knowledge cites, such as the Copenhagen Base in 1989, and the Craigmillar Community Information Service, Scotland in 1994 [7, 141].

The broadband city arrived with fiber-optic, a high-speed internet network that connects households and enterprises [7]. Some examples include Seoul, South Korea in

1997, Beijing, China in 1999, and Helsinki in 1995. The mobile/wireless city is a wireless network covering a city or part of it. Again, there are several examples of such cities: New York City in 1994 and Florence, Italy in 2006 [7, 141].

The digital or information city is a city that applies ICT to deliver local needs such as local development and transactions. Some examples are Austin, Texas from 1995 to today, Hull in the UK in 2000, and Trikala, Greece in 2003 [7]. In addition, the information city provides online services based on the data collected by distributed sensors [2]. The ubiquitous city is the global version of an information city, supporting the data flow from anywhere to everyone to provide ubiquitous services. Some ubiquitous city examples are New Songdo, South Korea in 2008; Dongtan, South Korea in 2005; and Masdar, the United Arab Emirates in 2008 [7].

The smart city unites the ubiquitous city with social infrastructure [122]. Several cities have been labeled "smart," such as Dubai (1999), Barcelona, Spain (2000), and Tianjin, China (2007) [7]. A city that considers the human, technological and institutional (community) dimensions to innovate high performance ICTs to increase the quality of life is typically a smart city [2]. The dimensions section explains smart city dimensions in detail. Also, smart city's definitions are explained in the definitions section.

The eco-city applies the ICT of the ubiquitous city with an environmental protection perspective [7]. The eco-city has widely varying definitions based on context. However, generally, the underlying design and strategies of eco-cities focus on the dimension of environmental sustainability [150]. Das et al. [6] represent an ecosystem as "an interdependent social system of actors, organizations, material infrastructures, and symbolic resources." Fig. 23 illustrates a smart city overview based on the technological classification.

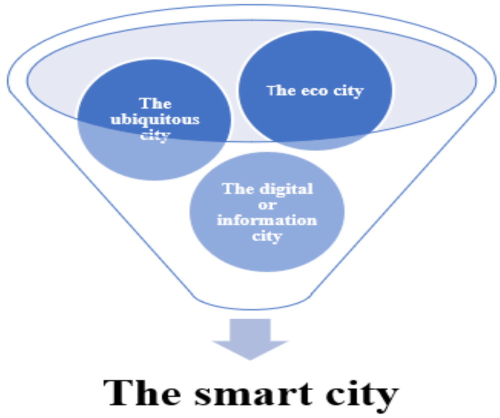

Fig. 23. The smart city term.

4.5.5 Smart Cities Based on Services

It is difficult to classify smart cities, as we see in the work of [141], who focused on the role of ICT in a city. When smart cities migrate from one class to another, the services they offer also change, hence, the classification of smart services arises. Consequently, this classification is based on smart city services and the way they perform. In 2013, Anthopoulos and Fitsilis analyzed 29 smart cities to determine their technological evolution and patterns [7] and proposed nine smart service groups (SGs). They based the nine proposed smart SGs on (Alcatel-Lucent, 2011) market-driven groups [7], which are shown in Table VIII.

TABLE VIII

NINE SMART SERVICE GROUPS [7]

Smart Service Group	Description
SG1: E-Government Services	City administration market-driven group
SG2: E-Democracy Services	City administration market-driven group
SG3: E-Business Services	Real estate market-driven group
SG4: E-Health and Telecare Services	Healthcare market-driven group
SG5: E-Security services	Public safety market-driven group
SG6: Environmental Services	Utilities market-driven group
SG7: Intelligent Transportation	Transportation market-driven group
SG8: Telecommunication Services	Real estate market-driven group
SG9: E-Learning and E-Education Services	Education market-driven group

In a city administration, a market-driven group covers all the e-government services in a city. It concerns public transactions with regard to the digital, smart, and ubiquitous city classes, while e-democracy services address consultation, polling, and voting. Again, these services relate to the virtual, digital, smart, and ubiquitous city classes [7].

In the e-business services group (SG3), all cities that provide business support or digital marketplaces are in the digital and smart city classes. A city that delivers e-health and telecare services (SG4) appears in the digital and smart city classes for the healthcare market-driven group. The ubiquitous city class is in the public safety market-driven group, which provides e-security services (SG5) to improve public safety. The environmental services group (SG6) addresses utility services, recycling, and environmental protection, which the ubiquitous and eco-city classes offer [7].

The (SG7) intelligent transportation group intelligently addresses public transportation, offered by the digital and smart city classes. Telecommunication services (SG8) are a different real estate market-driven group covering all connectivity methods offered by the broadband, mobile, digital, smart, and ubiquitous classes. Finally, the authors describe e-learning and e-education services (SG9) as an education market-driven group. SG9 covers education services such as the online classes and libraries offered by the smart and digital city classes [7].

4.6 Smart City Dimensions

Arroub at al. [2] have proposed three main smart city dimensions: technology, community, and people. The smart city is not just technology; it is also people and communities. The technology dimension includes all ICT features. The community dimension includes all the methods to increase the number of IT users, which some researchers describe as the institutional dimension. The people dimension considers the primary facts for city development. [120] also proposed the four dimensions of a comprehensive smart city. This dissertation follows the three-dimensional smart city. The multiple dimensions of smart cities represent one of the challenges of the smart city initiative [151].

The smart city is an a broad term encompassing many technologies and methods, which, in turn, leads to several smart city challenges. These challenges accrue for different reasons. Researchers have grouped these reasons into dimensions. [24] identified technology, people, and institutions as the three critical dimensions of a smart city. Smart technologies play a significant role in improving society by smartly and efficiently transforming services [152]. [24] proposed the smart city dimensions illustrated in Fig. 24.

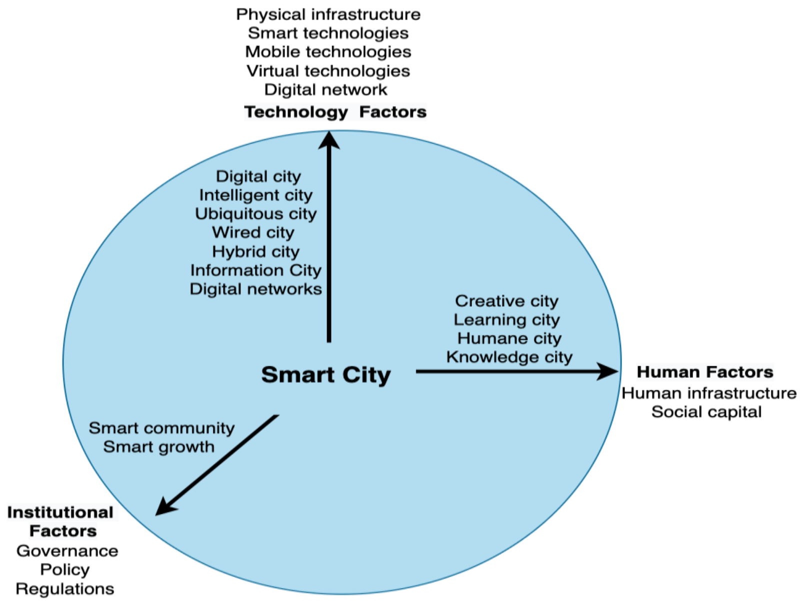

Fig. 24. The three dimensions of a smart city.

4.6.1 Technology Dimension (Technology Factors)

Researchers consider ICT to be the critical developer of smart cities, which means technology and infrastructures are the most critical dimension in implementing smart cities [111]. Moreover, almost all smart city definitions feature ICT as a prominent component. Thus, ICT plays a significant role in improving smart cities and solving their problems, especially in services that increase the quality of education, the economy, health, housing, transportation, security, and the environment [153].

The implementation of the technology differs from the point of view of the executor. The technology differs for public authorities or government, universities, and private companies. Dameri et al. [111] clarified three main technology perspectives. In the university domain, universities study smart city technologies, develop and experiment, and consider the costs involved. Sometimes they turn over their results to solution sellers. Private companies also play a significant role in enabling the technologies. Private companies apply the innovative solutions developed by universities to the smart city infrastructure. Finally, local government acts as a director, developing and implementing innovative solutions. Thus, public governments, universities, and private companies work together to implement smart cities.

ICT creates intelligent, scalable, and accessible infrastructure from which multiple agents can benefit [133]. For example, by using the ICT technologies to manage, control, analyze, and collect data from urban projects, monitoring systems, wireless networks, and mobile applications to increase citizens' quality of life, which is simply known as a smart city [133]. Nowadays, there are several highly advanced ICT applications such as the IoT, Big Data, AI, cyber-physical systems (CPS), data analysis, cloud computing, and blockchain technology.

All these technologies play a significant role in improving smart cities. Mobility, living, environment, citizens, government, manufacturing, architecture, and other smart city concepts become smarter through these technologies [16]. The ICT in smart cities plays an essential role in creating, inventing, testing, and experiencing new ideas to increase the quality of life. Moreover, ICT plays a significant role in "smartening" the object by adding sensing and automation features [2].

Smart cities collect substantial amounts of data from five main pillars, namely "Smart Economy," "Smart People," "Smart Environment," "Smart Mobility," and "Smart Living." Moreover, smart cities utilize different data sources and structures such as social media, health care terms, transport and distribution systems, videos, and the urban environment. To collect, store, analyze, and manage data with this kind of complexity, smart cities require advanced technologies [116].

In this regard, AI plays a significant role in combining systems and machine learning to make decisions and create insights for the smart city. Dubbeldeman and Ward [137] define Big Data as “data too large to be processed by traditional database management and analysis tools.” Smart cities rapidly generate data, making AI and Big Data technology necessary. The decision-making process of the systems requires high technology analytics; AI and Big Data can provide this kind of technology. However, implementing Big Data impacts organizational operations in the smart city domain. In this regard, researchers have proposed applying several algorithms, namely classification trees, logistic regression, neural networks, Markov chains, graph theory algorithms, and others to perform data mining [116].

AI and Big Data technologies play a significant role in developing smart cities. They provide flexible and real-time data processing that guides the decision procedures of the systems. Volume, velocity, variety, veracity, and value in Big Data require algorithms to process the data. Big Data analytics performed on smart city data help to find, detect and cluster patterns and dimensions [137]. The following subsections describe IoT, CPS, and blockchain technology.

4.6.1.1 IoT. IoT is a novel concept nowadays. However, the definition of IoT is still somewhat ambiguous as several definitions exist. Each definition represents a different perspective. Understanding these definitions by analyzing them is the best way to develop a universal IoT definition and also shed light on IoT's strengths and weaknesses. The following paragraphs explain IoT definitions based on well-known standards such as IEEE, European Telecommunications Standards Institute (ETSI), the Internet Engineering Task Force (IETF), and ITU [154].

IEEE is an international professional association focusing on engineering and technology fields. According to a report on IoT issued in March 2014, IoT is a "network of items—each embedded with sensors—which connect to the Internet" [155]. This definition only illustrates the physical part of IoT. IEEE P2413 aims to define an architectural framework and provide descriptions of IoT systems. IEEE P2413 considers the three-tiered architecture of IoT, as shown in Fig. 25.

Fig. 25. The three-tier architecture of IoT [154].

ETSI focuses on creating standards for ICTs. Internet technologies are one of its specialties. ETSI discussed IoT in terms of machine-to-machine (M2M) communication. According to ETSI, "M2M communication is the communication between two or more entities that do not necessarily need any direct human intervention. M2M services intend to automate decision and communication processes” [156].

The IETF focuses on networking designers and operators. The IETF defined IoT by defining the “internet” and “things.” According to the IETF report, “Internet of Things” [157], the essential idea of IoT is that IoT connects objects around us such as electronic, electrical, and non-electrical objects, thereby delivering excellent communication and services between them. The development of RFID tags, sensors, actuators, and mobile phones have created IoT. These components interact to enhance the service and make it accessible anytime, from anywhere [157].

IETF defines the internet as built on the TCP/IP protocol suite. Private and telecommunication networks are based on TCP/IP. From an IoT perspective, the internet considers the TCP/IP suite and no-TCP/IP suite as the internet. According to IETF, “things” are classified into three categories: people, machines, and information. Sensors and actuators are examples of machines; and clothes, food, medicine, and books are examples of information [157].

The ITU is centered on ICT. ITU defines IoT as a “ubiquitous network” [158]. When a network is available everywhere and at anytime, it is ubiquitously networked. According to ITU, IoT is a network “available anywhere, anytime, by anything and anyone” [154]. Fig 26 represents the ITU definition of IoT.

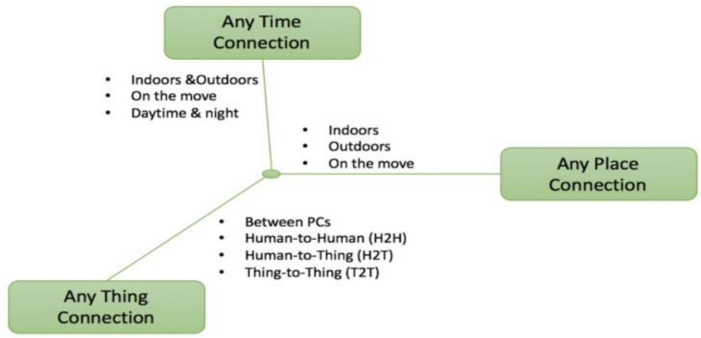

Fig. 26. ITU definition of IoT [154].

4.6.1.2 CPS. If we examine CPS more closely, we notice terms such as “components,” “control,” “physical,” “integration,” “processes,” “engineering,” and “systems.” All these terms construct CPS. Moreover, all these fields are involved in CPS, producing many research challenges and innovation opportunities.

There are six CPS characteristics that we can use to define CPS: hybrid systems, hybrid methods, control, component classes, time, and trustworthiness. In short, we can state that CPS is a combination of physical computing processes. CPS contains embedded computers, which are communication throw networks, to control and monitor the physical processes [159]. Many terms describe CPS, such as “embedded,” “engineered,” or “systems interacting with the physical.” Several examples of CPS include smart homes, traffic control, smart cities, smart grids, and supply chain systems. All of these examples interact with the physical world, which makes a system a cyber-physical system [159].

CPS contain communication devices and channels, sensors, machines, controllers, and processing units – each of which represents its own extensive research area. The primary role of CPS is monitoring and controlling objects in the physical world [159]. Consequently, timing plays a significant role in CPS. In this regard, collecting and transferring data also play an essential role. In CPS, communication and computation timing should support real physical world timing [160].

CPS represent powerful, comprehensive, interconnected systems with many components connecting and computing data using physical processes [161]. CPS can be systems such as physical, biological, or engineered systems. All CPS need communication and computational components necessary for control. Usually, real-time response and distribution are performed by the computational core. Therefore, we can describe the CPS behavior as "a fully-integrated hybridization of computational (logical) and physical action" [162].

All these definitions provide a clear picture of what CPS are. These definitions have several similarities, such as computing, physical components, and communication. Some also mention the real-time response, which means time is essential in some CPS.

4.6.1.3 Blockchain Technology. Hussien et al. [20] describe blockchain technology as "a decentralized digital ledger that provides an opportunity to record and share information in a community." In general, blockchain technology is a distributed ledger network that works as peer-to-peer and uses high cryptography technologies. Satoshi Nakamoto [163] proposed this technology in 2008. Nakamoto presented a paper entitled "Bitcoin: A Peer-to-Peer Electronic Cash System." The blockchain technology domain uses his paper as a white paper.

Technology has demonstrated its efficiency in managing, researching, and analyzing information in a smart city setting. There are several examples of the substantial role of technology in smart cities. For example, in health care, technology plays a significant role in storing, researching, and analyzing healthcare data to produce a clear patient record (e.g., Electronic Health Record). In another scenario, monitoring health data and secure, stable communication play an essential role in improving the health care sector [2].

However, these services have security, privacy, and accessibility issues. Blockchain technologies have the potential to minimize these issues. They enable autonomous interaction with the smart city infrastructure. Transferring and processing data, and providing accessible data are features of blockchain technology [133]. The blockchain chapter explains the blockchain technology in detail.

4.6.2 Community Dimension (Institutional Factors –Governance)

Institutional factors, community, or governance play the same roles in the smart city domain. Institutional factors illustrate smart city governance by establishing collaborations, citizen engagement, and participation. Public and government engagement play significant roles in city smartness [124]. Governance and a sustainable economy significantly impact human, IT infrastructure, and smart sources management [123]. Lynn et al. [164] define governance as "as regimes of laws, administrative rules, judicial rulings, and practices that constrain, prescribe, and enable government activity, where such activity is broadly defined as the production and delivery of publicly supported goods and services." According to [164], the primary governance roles constitute rules and apply them to processes and information exchange to attain smart cities' goals and objectives.

Chourabi et al. [117] analyzed a study on e-government challenges conducted by [165]. The study addressed the stakeholders' relationships as the key to the smart city project's success. Four stakeholder relationship issues emerged from this study: stakeholder cooperation, supportive leadership, structuring alliances, and multiple jurisdictions. The ICTs have a significant impact on minimizing these challenges, thus, leading to the emergence of smart governance as a result of this involvement. All ICTs, people, resources, and social norms play a significant role in supporting the city's governance. The governance dimension in the smart city consists of several factors, such as collaboration, leadership, participation, partnership, communication, data exchange, accountability, and transparency [117].

Other researchers have addressed e-participation, e-services, e-consultation, ICTs, open data, e-decision-making, and smart governance as smart city governance initiatives [151]. Transparency and stakeholder involvement are also challenges for smart city governance. Smart city governance also faces complex problems in changing the existing political mindset, especially in the developing phase. Some smart governance risks also exist, such as systems and data security, accuracy, accessibility, and quality. Smart cities rely on smart governance as one of the main dimensions to innovate smart cities [151].

4.6.3 People Dimension (Human Factors –Learning)

Smart city scholars use several terms to explain the people dimension, such as the "human dimension," "human factors," and "social." The human factor plays a significant role in enhancing city smartness [124]. It also plays a pivotal role in creating a successful smart city. The human factor illustrates the people's role in the smart city domain. According to [124], the smart city results from "endowments and activities of self-decisive, independent, and attentive inhabitants." This quote illustrates the importance of the citizens' education on a city's smartness. The smart city is more comprehensive than the ubiquitous city because of its social infrastructure, which represents the human dimension

[122]. The smart city is not only limited to advanced ICT. Several smart cities follow the user-centric approach based on citizen involvement [130].

Concilio and Rizzo [166] illustrate the vital role of humans in the smart city domain because the city is not smart if it is not taking advantage of its people. The concept of the “Human Smart City” appeared in 2013 [123]. In these smart cities, ICT plays an essential role in empowering people, which helps people engage in the city's decision-making processes. Technology also has a significant role in creating human-centric innovation systems. Lately, the human roles in smart cities have been increasing, and technologies make that engagement more straightforward, efficient, and secure [123, 167]. According to [168], all smart cities should be citizen-centric. Currently, most smart cities ignore or minimize the needs of the marginalized. They o

nly focus on the active and fully abled [169]. Several smart city models make the human dimension their central point—for example, multiple stakeholders, as explained in the smart city models’ section, and multiple analytical benefits.

Wolff et al. [170] explain the human role in smart cities. They see the human (citizens) role as “citizens as innovators,” not limited to “citizens as users,” or “citizens as participants.” Chourabi et al. [117] explain the importance of addressing people as a critical aspect of smart cities. As mentioned in previous sections, the main goal of smart cities is to increase the quality of life of their citizens, which makes educated and participatory citizens extremely important. Smart city scholars have proposed several ways to educate and involve citizens in the process (as stakeholders). In addition, the trade-off (balancing) between citizens is essential. These points remain a challenge in the smart city domain.

4.7 Smart City Characteristics and Components

Barrionuevo et al. mention five characteristics that contribute to a smart city's intelligence: economic, human, social, environmental, and institutional characteristics [152]. Similarly, Albino et al. recognized five characteristics that play the same role: IT, education, environment, quality of life, and governance [152]. Most smart city models have recurring characteristics, but most contain the following six proposed by Arroub et al. [2]: smart economy, smart governance, smart mobility, smart environment, smart living, and smart people. Fig. 27 illustrates the characteristics of a smart city.

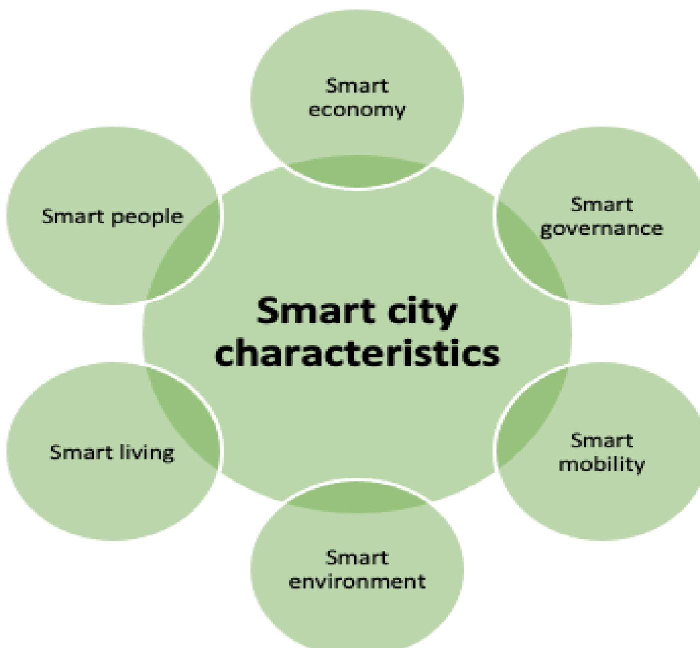

Fig. 27. The characteristics of a smart city.

In comparison, Kogan and Jun Lee recognized ICT working with citizen engagement and government as the two main characteristics of a smart city [171, 152]. Furthermore, all the technologies involved in smart city research and development, such as IoT, CPS, AI, machine learning, data analysis, and Big Data, are regarded as technology stakeholders [152].

Hollands states that "progressive, smart cities must seriously start with people and the human capital side of the equation rather than blindly believing that IT can automatically transform and improve cities" [172, 152]. Therefore, governance and citizen engagement are essential characteristics of successful smart cities [152].

Commonly, smart city models consist of eight main components: smart infrastructure, smart transportation, smart environment, smart services, smart governance, smart people, smart living, and a smart economy [7].

The first component, a smart infrastructure, means applying smart technology such as IoT and smart grids to water and energy networks, streets, buildings, and other city facilities. The second component, smart transportation, means monitoring and controlling transportation networks or transportation systems in real-time. This component is also known as smart mobility. The third component, a smart environment, incorporates innovation and ICT to protect natural resources and manage environmental systems. There are several environmental system examples, such as waste management systems and pollution monitoring systems. The fourth component, smart services, apply technology and ICT to increase the city's health, education, tourism, and safety.

The fifth component is smart governance. The smart government establishes smart technology for participation and engagement in the urban space. The sixth component is the measurement used to enhance people's innovation activity and creativity, that is, smart people. The seventh component, smart living, is any innovation that plays a role in improving the citizens' quality of life. The eighth component is a smart economy, which plays a significant role in strengthening business development and urban growth by applying technology and innovation.

4.8 Smart Healthcare

Researchers have examined several smart healthcare categories: e-healthcare services, healthcare monitoring, accessible data, privacy, security, quality, efficiency, and delivery. Gupta [173] listed eight smart city dimensions: smart citizen, smart energy, smart technology, smart infrastructure, smart mobility, smart building, smart healthcare, and smart governance. The characteristics of a smart city also play a significant role in smartening the healthcare system.

In this regard, the smart economy characteristic is composed of five common characteristics: a smart economy is innovative, digital, competitive, green, and social. Arroub et al. [2] clarified these characteristics. A smart economy provides innovative ways to increase productivity and reduce costs. The digital characteristic means applying ICTs widely in the economy. The competitive characteristic means being open to new knowledge and innovation concerning quality, profits, and efficiency. The green characteristic relates to the preservation of the environment by using sustainable resources. Finally, the social characteristic plays an essential role in increasing the quality of life and welfare of citizens [2]. Researchers have also cited several smart economy categories: the penetration of m-commerce, GDP per head of city population, level of innovation and productivity, the employment rate in the high technology industry, foreign direct and domestic investment, and cost reduction [153].

The smart environment characteristic also plays a vital role in the healthcare domain, which means having innovative environmental infrastructures to increase sustainability. For example, the energy resources must be natural and green [2]. Researchers describe several smart environment categories: waste management, air pollution, green areas, water quality, and emission control systems [153]. Similarly, smart governance plays a significant role in managing projects and initiatives, unlike traditional governance. Traditional governance is known as “regimes of laws, administrative rules, judicial rulings, and practices that constrain, prescribe, and enable government activity, where such activity is broadly defined as the production and delivery of publicly supported goods and services” [2]. In contrast, smart governance uses innovative policies, technologies, resources, business models, and social knowledge to manage city governance activities [2]. Researchers include several smart governance categories such as the availability of integrated e-government services, social media involvement, open data (open government), supportive government policy/regulations, and the enhancement of public-private partnerships [153].

Smart living is an innovative way to make living easier, safer, and cheaper [2]. Researchers cite several smart living categories such as public safety, privacy, security, healthcare services, level of internet access, education and cultural facilities, touristic attractiveness, affordable housing facilities, participation in public life, and life recreation [153].

Finally, smart mobility has a significant impact on healthcare. For example, in 1964, British architect Ron Herron proposed the “Walking City.” Then, in 2007, David Miller proposed the “Transit City,” which was a solution to reduce population density by integrating railway and tram routes [2]. In addition, new technologies such as IoT play a significant role in improving smart mobility [2]. Researchers identify several smart mobility categories: traffic, vehicle management, internet of vehicles, intelligent parking systems, and sustainable, safe transportation systems [153]. For example, Urban Traffic Control and Traffic Management Systems (TMS) have evolved by using innovative IoT technology to improve their service.

4.9 Smart City Architecture

Smart city architecture defines the information structure and ICT management [7]. This term has been used to explain or define the systems and buildings' physical structures, which shows the relationships between their components [7]. The architecture should be built based on the client's needs. In other words, the architecture consists of elements that work together to meet the client's needs.

Anthopoulos [7] defined the features of ICT system architecture. The ICT system architecture can be used to define the system and its functions and relationships. It also provides strategies over time to guide the system's design and evolution. The architecture plays a significant role in protecting the system's components. All the components in a system define the hardware, software, data flow, and management, which provide alternative architectural perspectives [7].

In general, hardware architecture describes the physical system's components and their relationships [174]. For the software or application architecture, structures are based on technology definitions [7]. The software architecture also plays an important role in specifying the software components and their interrelationships that meet the system requirements [174]. Data flow or information architecture describes the way the system uses the information to meet the organization's strategic and operational requirements [7]. This architecture helps filter the information or meet the business system architecture's needs, which plays an important role in analyzing the information to meet those needs. Ultimately, the technical architecture defines all the environments and infrastructures of the systems [7].

Based on the aforementioned ICT system architectures, the technical architecture plays a major role in determining smart city creation [7, 113]. It illustrates the request for the environmental structure that meets the system goal. It also establishes the technological standards and creates a framework for making technological decisions. In addition, the technical architecture provides strategic technical advice that keeps the system organized. The technical architecture illustrates the organization's needs and issues and develops its governance structure [7]. Almost all smart city models have six recurring components: smart economy, smart transportation, smart governance, smart environment, smart healthcare, and smart living. All these components are connected, and they require the ICT infrastructure to collect and analyze the data to deliver smart services to the city. Smart governance is needed to coordinate the smart services to achieve the smart city mission [7]

4.10 Smart City Models

Smart city models are beneficial and can be used to realize the contributing actors and components. They can also be used for evaluating or measuring, analyzing, comparing, and verifying. These functions are beneficial for developing, implementing, and improving smart cities [111]. There are a number of smart city models. For example, business models, the smart city wheel model, International Business Machines’ (IBM) smart city nine pillar model, ITU’s framework for smart city analysis, the smart city initiatives framework, and the smart city as a complex system represent some of the smart city models. Anthopoulos et al. [175] also discussed several models, such as ISO 37120 Sustainable Development of Communities: Indicators for City Services and Quality of Life, smart city dimensions, dimensions of city prosperity, and the IBM smarter city equation. The following subsections detail these models.

4.10.1 Business Model

In the smart city domain, business models have a significant role in improving the citizens’ productivity without requiring economic benefits, and it was not used for value proposition [176]. The value model supplies a context for the provided services. The value proposition, infrastructure, and network play a significant role in strengthening the business model. The strategies impact the business model, which helps to build a long-term relationship between government, citizens, and companies, which leads, in turn, to a comprehensive vision that produces investment opportunities and engaged citizens. An innovative business model can make a city smarter. A successful business model covers the process, people, technology, and legal aspects and create a model with a context [176].

Shetty et al. [176] provided a literature review on smart city business models. There are several business models applicable for the smart city domain. In addition, there are several business model patterns such as sustainable, innovative, circular, smart, and theoretical patterns.

Shetty et al. [176] listed several definitions of business models. [177] defined the business model as "an architecture of the product, service, and information flows, including a description of the various business actors and their roles; a description of the potential benefits for the various business actors; a description of the sources of revenues." This definition is based on two points: architecture and revenue. Rappa [178] illustrates the business model's role in positioning the company and helping it to earn money. In addition, the model provides ways for the company to maintain itself and grow—this definition is based on the revenue. Leem et al. [179] also defined a business model based on revenue as strategies that guide the establishment and management of high-level business processes.

In contrast, Richardson [180] defined a business model based on business marketing strategies and explained it as a framework with three primary elements: value proposition and creation, system delivery, and value capture, which act as a guide to execute and complete all the activities in the system. This technique provides the highest value for customers. In [181], a business model articulates the value proposition and structures revenues and costs by providing logic and data. Finally, he builds his definition based on revenue business marketing strategies [176].

Following in [182], Wirtz et al. defined a business model based on architecture and revenue. They defined the business model as "a simplified and aggregated representation of the relevant activities of a company" [176]. The model helps to describe the marketable information, products, and services a company generates. To achieve the superior goal of creating competitive advantage, the business model should be dynamic and adopt any internal or external changes over time [176].

4.10.2 Smart City Wheel Model

Bravo [183] discussed the "smart city wheel," which Boyd Cohen proposed in 2013. Boyd Cohen proposed the smart city wheel to track a smart city's progress. The smart city wheel consists of smart governance, smart environment, smart mobility, smart economy, smart people, and smart living [2]. [124, 135, 183] explained the six main keys in the "smart city wheel." In the smart governance indicator, policy, transparency, and e-government integration should be available. In the smart environment indicator, cities should be green by applying sustainable urban planning. In the smart mobility indicator, cities should deliver mixed-modal access. In the smart economy indicator, encouraging entrepreneurship and innovation to increase productivity is critical for a smart economy. In the smart people indicator, education plays a significant role in innovating and supporting society. Finally, the smart living indicator has a role in improving a smart city's culture, safety, and health.

According to European Smart Cities [136], a smart city performs well in terms of the economy, governance, living, mobility, environment, and citizenship [135]. The smart city wheel model covers these aspects. According to [2], every city's needs and challenges are different, therefore, establishing the city's vision is the priority. Following this, the city can establish the indicators.

4.10.3 IBM Smart City Nine Pillar Model

In this model, the starting point is regarded as the essential part of establishing a city's vision [2]. For example, IBM proposed a three-dimensional vision consisting of three pillars: people, infrastructure, and operations. According to this vision, there are also three services: people services, which consist of education, healthcare, and social programs; infrastructure services, which consist of energy, water, and transportation; and operations services, which are city governance and public management [2].

The smart city is based on three main pillars: people, infrastructure, and operations in this model. In terms of people, a smart city should involve the community in the decision-making process. ICT has an essential role in the infrastructure pillar and plays a significant role in coordinating activities and services. It also improves the citizens' engagement. Finally, the operations pillar ensures that the information flow reaches all the smart city stakeholders [183].

4.10.4 ITU Smart Sustainable City Key Performance Indicators

The SSC key performance indicators (KPIs) model was proposed by [184]. This model focuses on sustainability, productivity, equity, and infrastructure development [175]. This model provides general guidance for smart sustainable cities by applying KPIs. These KPIs measure the impact of using the ICTs in smart cities. The KPIs can be beneficial in supporting the SSC and its stakeholders to reach their goals. The ITU SSC KPIs model has six ICT-related indicators: ICT, environmental sustainability, productivity, quality of life, equity and social inclusion, and physical infrastructure.

4.10.5 Framework for Smart City Analysis

Lee et al. [122] proposed a framework for smart city analysis. The framework focuses on urban openness, service innovation, partnership formation, urban proactiveness, smart city infrastructure integration, and smart city governance [175]. The proposed framework contains several definitions, dimensions, sub-dimensions, and descriptions [122].

4.10.6 Smart City Initiatives Framework

Chourabi et al. [117] proposed a smart city initiatives framework that consists of internal and external levels [145]. The initiatives framework illustrates the relationships between administration, ICT, policy context, people, economy, built infrastructure, environmental factors, and other factors with smart city initiatives [117]. This framework determines which factors meet the smart city initiatives. The framework goal characterizes the smart city vision, design, services, and emerging challenges.

4.10.7 Smart City as a Complex System

Researchers have proposed several models to study and analyze the complexity of cities to improve their functionality, safety, security, services, and smartness [169]. For example, a planning framework for green space [185], the city as a complex adaptive system (an action-oriented) [186], multi-stakeholder [187], “cityDNA” framework [8], and a pattern of collaborative networking [9] are some models that consider the smart city as a complex system.

Several researchers consider the smart city to be a complex system (system of systems) [2, 3, 4, 5, 6]. Furthermore, multi-stakeholderism is considered a challenge in a smart city, and researchers have proposed several models to minimize this challenge [169]. These models are multi-stakeholder [187], collaborative, and participatory approaches [188, 189].

The multi-criteria evaluation models also play a major role in designing decision-making processes in the smart city. Some of the proposed models are [190, 191, 185].

The “cityDNA” framework was proposed by [8]. The “cityDNA” reflects the city’s state of health by taking a snapshot of the "cityDNA.” It works similarly to human DNA. This framework uses KPIs. It compares the city data with the ISO 37120 Standard to analyze the city profile. It is worth mentioning that the city profile changes over time. The main goal of this framework is to detect interrelations between the smart city’s dimensions. Therefore, the “cityDNA” framework represents a data-driven framework.

Rădulescu et al. [9] proposed a model for a pattern of collaborative networking. They created the model to enhance sustainability in smart cities. They applied the logic of the complex adaptive system (CAS) in this model. In addition, the model uses social network analysis. This model's results illustrate the role of each group of competencies in enhancing smart city sustainability. Collaborative networking plays a significant role in analyzing the interconnections between the eight competency groups.

4.11 Smart City Requirements

Giffinger et al. [124] proposed six characteristics to measure a city’s smartness. They proposed economy, people, governance, mobility, environment, and living as the citizens’ and communities’ tracking measurements [4]. People and communities need to specify their requirements, and these requirements are different from one city to another. Researchers have discussed several smart city requirements. This section identifies the most endorsed requirements for smart cities. By examining the smart city from a requirements engineering perspective, a smart city is a system of systems. In other words, the requirements for smart cities are comparable to complex systems [4].

Daneva and Lazaro [4] analyzed 32 selected publications. As a result, they classified smart city requirements into four main classes: end-to-end experience, architectural, security, and infrastructure requirements. This classification considers three kinds of smart city systems, which are instrumented, interconnected, and intelligent systems [147, 192]. The instrumented system is a smart city setting that responds to capture and integrate the live real-world and virtual data [4]. The interconnected system is a smart city setting that creates an end-to-end integration process for information [4]. Finally, an intelligent system is a smart city that analyzes information to make intelligent decisions and actions [4].

4.11.1 End-to-End Experience

End-to-end experience addresses the historical behavior of the smart city [4]. End-to-end experience requirements cover all of a system's components, from the user interface to data storage. They also provide the requirements for complex systems from beginning to end. The end-to-end arrangements play a significant role in cost effectiveness [193]. These end-to-end experience requirements will be explained based on the three smart city system types: instrumented, interconnected, and intelligent systems.

4.11.2 Architecture

Architecture requirements describe the elements of the smart city's ICT systems and how they work together [4]. These architecture requirements will be clarified based on smart city system types. The architecture requirements cover instrumented systems, interconnected systems, and intelligent systems.

4.11.3 Security and Privacy

Security and privacy requirements describe the technology and policy aspects, including information security, data protection, data sharing, and privacy [4]. These security and privacy requirements will be filtered based on the smart city systems [4]. The security and privacy requirements cover the smart city system types.

4.11.4 Infrastructure

Infrastructure requirements describe the interaction and the relationship between elements in a subsystem and between subsystems [4]. The infrastructure requirements will be categorized based on the types of smart city systems. The infrastructure requirements cover instrumented systems, interconnected systems, and intelligent systems.

Smart city growth must consider three critical points: sustainability, smartness, and inclusiveness. Sustainability means the improvement processes must consider the relationship between the city and the environment. In other words, it must consider the green economy. Smartness means being aware of the context (e.g., context-aware economy and governance). Finally, inclusiveness means high-quality cohesion for all smart cities [2].

4.12 Smart City Challenges

All the smart city studies shed light on seven main challenges: the economy, urban infrastructure, city management, social integration, environmental and life qualities, good governance, and security [7]. As previously mentioned, smart cities have alternative approaches to conceptualizing the objective of the city, which lead to different challenges. Some of the most widespread smart city challenges are data storage, processing, and availability issues. Researchers have proposed several methods to resolve these issues [6].

Smart cities experience environmental, economic, technological, and social challenges. Each smart city faces several challenges. The challenges in a smart city are complex. For example, smart mobility has its challenges as does health care. Furthermore, there are common smart city challenges: security, privacy, power, and management.

Universities study and teach innovative technological solutions for smart cities. Unfortunately, these technological solutions are not always perfect for the challenges faced by smart cities, especially with their range of heterogeneous citizens and services [111]. The smart city technology section provides further explanation of this subject .

In smart mobility, developing transport that meets privacy, independence, freedom, flexibility, and other citizen needs using sustainable and green sources is the most significant challenge that smart mobility faces [2]. Health care has a vested role in improving citizens’ well-being and quality of life. Smart health care in a smart city setting aims to innovate solutions using highly advanced technologies. Smart health care provides solutions to health sectors that will improve health care services and quality while considering the cost and the environment [2]. Nowadays, telecare or telemedicine has become more feasible because of smart health care technologies. However, these technologies face several challenges. In addition, there are also health service privacy, security, mobility, quality, and speed challenges.

New security and privacy issues are considered obstacles to citizens' approval of smart city applications [4]. IoT, AI, Big Data, and other ICT areas create the smart city sectors. For example, IoT technology plays a significant role in linking the physical and virtual worlds with intelligence, but these technologies face security and privacy issues, despite considerable work to combat these issues [2]. The privacy of personal data is a controversial issue in the smart city domain. Chourabi et al. [117] addressed the privacy of personal data as both security and privacy challenges.

Smart city management is another of the smart city challenges. Worldwide, researchers have been working to provide an improved way to increase the sufficiency of the management of urban areas. Several smart city models target this challenge, focusing on technology, connectivity, sustainability, security, safety, and mobility [2]. The smart city must manage multiple sources of Big Data to collect, analyze, store, and deliver data to function effectively. Consequently, we require innovative methods to address these management challenges, especially those that require advanced computation and scalability. In addition, these innovative methods must contend with modern challenges and technologies [133].

There is also a shortage of consolidation among government systems [117]. Collaboration, leadership, participation and partnership, communication, data exchange, service and application integration, accountability, and transparency are the main challenges in managing smart cities, which cause the lack of integration within a smart city's systems [117]. Additional challenges include identifying citizens as key stakeholders, involving citizens in the process, data storage, processing, availability, lack of knowledge regarding interpretability, the price of installation, and the management of smart city systems.

4.13 Smart City Assessments

Several assessments can be applied in the smart city domain. ISO is one of them. It has proposed several standards that explain the requirements for developing smart city infrastructures [125]. Similarly, the BSI proposed “PAS 181,” which is a framework for smart city transformation [110, 132]. In addition to these standards, there are several methods to measure the success of an implementation. Finally, there are well-known ways such as ranking metrics and assessment frameworks (known as maturity models) [110]. The main role of the maturity model is to define the maturity levels for a class of objects. It provides characteristics and different criteria that need to be fulfilled to reach a particular maturity level [194].

Leonidas G. Anthopoulos proposed two hypotheses to interpret the analysis of the evolution of the smart city [7]. First, no general smart city technologies can be applied in all smart cities. Each smart city has its own course of evolving technology. Second, the smart city technological evolution is not interesting for all city classes. Environmental e-service appears to be the most interesting technology [7].

Aljowder et al. [110] analyzed 22 maturity frameworks. They considered the United Nations smart city sustainable development goals (SDGs). As a result of their work, 9 out of 22 frameworks were comprehensive models. Most of the models focus on technology components with less consideration for the environmental aspects. The comprehensive maturity model plays a significant role in evaluating the smart city model or a city's smartness.

As many people recognize, smart cities are needed to find innovative ways to increase the citizens' quality of life. Nowadays, smart city technologies greatly impact city planners and decision-makers. They make resources management, safety, security, energy, health, and education efficient and more intelligent [110].

Researchers have proposed several maturity models. Some of them focus on the smartness of the cities by applying governance systems. These models derive from different international perspectives, meaning they are difficult to fit to specific smart city requirements. Each city has its requirements and these differ from one city to another [110]. The United Nations proposed the SDGs)for cities adopted by the global Vision 2030 [110].Therefore, to construct a general smart city model, Aljowder and Kurnia examined the relationship between the maturity models' components and the SDGs [110].

In contrast, Anthopoulos and Fitsilis proposed the reason for this evolution [7]. They mention that the organization, business, and facility's operational goals (political, social, legal, environmental, and economic) are the key reasons for the development of smart cities [195, 7]. Nevertheless, this theory requires validation through further testing [7]. An effective smart city implementation should consider three aspects: technology, humans, and institutions. Some scholars represent their frameworks as conceptual or architectural, which can simplify and improve the assessment [110].

4.14 Summary

Incorporating smartness into transportation, healthcare, education, governance, mobility, and economic development plays a major role in a city obtaining a high state of efficiency and quality of life for its residents [7, 105]. ICT has a phenomenal impact on increasing the smartness level of a city and addresses how the term “smart” relates to efficiency and knowledge [6]. The term “smart city” appeared in the early 1990s [110, 7]. However, the concept behind the smart city appeared in the 1960s. This dissertation presents many smart city definitions dating from 1994 to today, which illustrates that the smart city definition is still uncertain. However, most of the definitions center around applying ICT and innovative solutions to increase the quality of life. Each one of these aspects represents a vast domain of its own. The objective of the city also (services, management, infrastructures, environment, security, economy, and society) plays a significant role in defining a smart city.

All smart cities have an essential goal: enhancing the citizens’ quality of life [111]. Smart cities have evolved in terms of definitions, models, ICT, and developmental generations [7]. For example, smart cities have evolved from cybernetically planned cities [7] to blockchain cities [18]. Cohen [146] proposed three main generations of smart city development [145]: tech-driven, city-driven, and citizen co-creation. Equally, the smart city has classifications based on area and systems, stakeholders’ vision, learning, technology, and services [7, 148, 149, 141]. Based on this evolution, scholars have proposed several smart city dimensions. We considered the three-dimensional approach [24]: technological, institutional, and human. Each of these dimensions is a research area in the smart city domain.

Understanding smart city characteristics is key to understanding what a smart city is. Smart city researchers have proposed that the smart city has several characteristics. For example, Barrionuevo et al. proposed five characteristics of a smart city: economic, human, social, environmental, and institutional characteristics [152]; while Arroub et al. [2] proposed six characteristics: smart economy, smart governance, smart mobility, smart environment, smart living, and smart people. These characteristics also play a key role in the architecture of smart healthcare systems in a smart city.

Smart city models are valuable for understanding which contributing actors and components play a vital role in evaluating, analyzing, comparing, and verifying the smart city. Smart city scholars model smart cities as complex or non-complex systems. The following are familiar smart city models: business models, smart city wheel model, the IBM smart city nine pillar model, ITU framework for smart city analysis, and the smart city initiatives framework. There are also models for the smart city as a complex system: the city as a CAS (action-oriented) [186], multi-stakeholder model [187], the “cityDNA” framework [8], and a pattern of collaborative networking [9]. However, none of these models are general.

CHAPTER 5

BLOCKCHAIN

5.1 Introduction

Generally, blockchain technology reduces centralized parties and increases security and accessibility [20]. In the blockchain, the transactions store data in blocks, and these blocks are linked to each other by hashes. This technique is what gives the blockchain its name [19]. This chapter describes the background, definitions, and characteristics of the blockchain, the taxonomy of blockchain systems, the blockchain mechanism, smart contracts, blockchain layers, the blockchain city, and blockchain challenges.

5.2 History and Definitions of Blockchain Technology

A centralized structure used to be the primary structure in organizations and systems (e.g., a bank), where parties need a trusted third party to conduct transactions. However, the centralized structure has several problems, such as unauthorized modifications in the security domain, single point of failure in the reliability domain, and bottlenecks in the performance domain [19]. These issues have played major roles in the emergence of blockchain technology.

The central point of blockchain is to provide a channel for unknown participants to connect with each other securely, without the need for a trustworthy third party [19]. Generally, the blockchain is an organized list of blocks. Every block has a number, data, cryptographic hash, previous block's hash, and nonce [196]. The main role of the previous block's hash is to build a chain of blocks by referencing the previous block in the chain, which makes the blockchain difficult to modify, hack, or manipulate [19].

In other words, a ledger contains data records that are listed as "blocks." Each block relates to the previous block. All the blocks are time-stamped and cryptographic, which forms the blockchain [197].

Nakamoto [163] presented the first example of a cryptocurrency in his paper "Bitcoin: A Peer-to-Peer Electronic Cash System." Generally, Bitcoin is a decentralized distributed electronic payment system, where the parties can trust each other without the need to use a third party. However, the original idea behind blockchain technology goes back to 1991 [198]. In their paper, [198] discussed how to time-stamp digitally distributed documents, and this paper represents the first appearance of the blockchain concept. Almost all blockchain definitions use the term "ledger." The term "ledger" is a Dutch term, which goes back to the 15th century and refers to a book placed permanently in a specified spot [17]. Table IX lists some blockchain definitions.

TABLE IX

BLOCKCHAIN DEFINITIONS

Reference	Definition
[17]	"Blockchain is a shared database or distributed ledger, located permanently online for anything represented digitally, such as rights, goods, and property."
[19]	"A blockchain is a distributed ledger that records all the transactions that have ever occurred in the blockchain network. This ledger is replicated and shared among the network's nodes."
[20]	"Blockchain technology is a decentralized digital ledger that provides an opportunity to record and share information in a community. Each entry is transparent and searchable, thereby enabling community members to view its history."

[199]	"A blockchain, by design and definition, is a particular type of database."
[200]	"A blockchain is a chain of transactions or it is defined as a distributed ledger maintained by many organizations and consists of users."
[197]	"Blockchains are shared and distributed data structures or ledgers that can securely store digital transactions without using a central point of authority."

5.3 Characteristics of Blockchain Systems

5.3.1 Network Permission

In the network perspective, there are two types of blockchains: permissionless and permissioned (a.k.a., public and private). Generally, it describes the relationship of the nodes that run on the blockchain network for transaction or validation purposes [20]. Bitcoin, Zcash, and Ethereum are examples of public blockchains, and Hyperledger Fabric and R3 Corda are examples of private blockchains [19]. The public blockchain is known as a permissionless blockchain, which means that any member can contribute to the validation process, which can be anyone via the internet [20]. In contrast, the private blockchains select nodes to manage the blockchain network, which are known as miners [19].

There is a third type of blockchain that some researchers categorize under the private blockchain, which is a consortium blockchain. This type of blockchain results from the integration of public and private blockchains, but it does not resemble the private blockchains [20]. The consortium blockchain is a hybrid type and partially decentralized [20]. This classification makes two types of blockchain nodes. Table X illustrates the differences between these types. In addition, the private and public blockchains work differently, as shown in Fig. 28 below.

TABLE X

BLOCKCHAIN NODES

Full node	Light node
Save a full copy of the ledger Verify a transaction	Save a full copy of the ledger

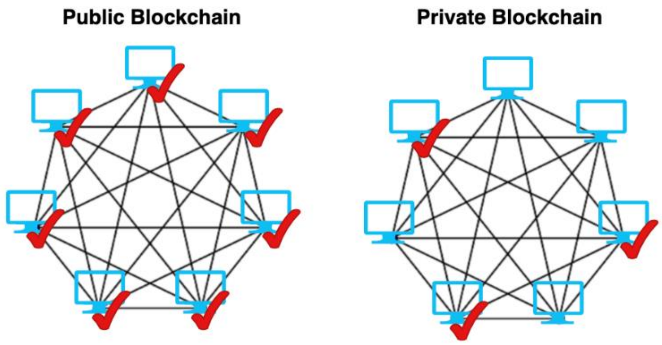

Fig. 28. Private vs. public blockchain representation [197].

By comparing private blockchains with public and consortium blockchains, it is clear that private blockchains perform faster than public blockchains [19]. Each type of blockchain has its advantages and disadvantages—Table XI illustrates the differences between these types.

TABLE XI

BLOCKCHAIN TYPES [19]

Type	Public	Private	Consortium
Nature	Federated & Secure	Governed & Filtered	Governed & Filtered

Consensus Protocol	PoW, PoS, DPoS	PBFT, RAFT	PBFT
Transaction Processing	Time-consuming	Moderate	Small
Approvals	Robust & Unverified	Confidential & Pre-verified	Confidential & Pre-verified
Transparency	Low	High	High
Utilization of Energy	Extraordinary	Lower	Lower
Scalability	Extraordinary	Extraordinary	Low
Example	Bitcoin & Ethereum	Bankchain	Multichain & Blockstack

5.3.2 Consensus Protocol

Blockchain uses the consensus protocol to achieve agreement on the blockchain state [19]. There are several consensus algorithms or protocols that validate the blockchain process. The consensus algorithm's main role is to compare the blocks and ascertain which to accept as valid [197]. This shows the significant role the consensus protocol performs in the blockchain. Some consensus protocols are Proof-of-Work (PoW), Proof-of-Stake (PoS), Delegated Proof-of-Stake (DPoS), Proof-of-Service, Byzantine Fault Tolerance (BFT), Proof-of-Authority (PoA), and Proof of Elapsed Time (PoET) [19, 201, 202].

Table XII illustrates the differences between the blockchain platforms and their characteristics. Some blockchains are designed for cryptocurrencies, but not all cryptocurrencies run on a blockchain [19]. For example, the IOTA is a new generation of cryptocurrency that does not run on a blockchain [203]. The mining method in the IOTA is a directed acyclic graph (DAG), known as Tangle, and the consensus method is the PoW [204].

TABLE XII

DIFFERENT BLOCKCHAIN PLATFORMS [19]

Blockchain Platform	Network Permission	Consensus Protocol	Cryptocurrency Support	Smart Contract Support
Bitcoin	Permissionless	PoW	Yes	No
Ethereum	Permissionless	PoW/PoS	Yes	No
Zcash	Permissionless	PoW	Yes	Yes
Litecoin	Permissionless	PoW	Yes	No
Dash	Permissionless	PoW/Proof-of-Service	Yes	Yes
Peercoin	Permissionless	PoS	Yes	No
Ripple	Permissionless (Controlled)	RPCA	Yes	No
Monero	Permissionless	PoW	Yes	Yes
MultiChain	Permissioned	Round-Robin	No	No
Hyperledger	Permissioned	Various protocols (e.g., Kafka, BFT, and PoET)	No	No

5.4 Blockchain Mechanism

Blockchain works on a peer-to-peer system, which means the nodes on the network are connected to each other. The nodes' role depends on the blockchain structure. Generally, the blockchain nodes are responsible for making and sending new transactions and maintaining the blockchain [19]. Nodes in the peer-to-peer network can be a company or a person.

To understand the blockchain mechanism, several important terms must be clarified, such as peer-to-peer distributed network, immutable ledger, mining, and consensus protocol. Fig. 29 illustrates the overview of the blockchain mechanism. The blockchain mechanism begins with a user generating a transaction and usually sending it to the "transaction pool." Then the mining process begins by selecting a transaction to create a block. Following this, the verification process works to validate the block before adding it to the blockchain. The blockchain's database is immutable and contains blocks with transactions that are associated with their previous transactions via a cryptographic hash tree [20]. This explanation is based on the analysis of [20, 19, 205, 197].

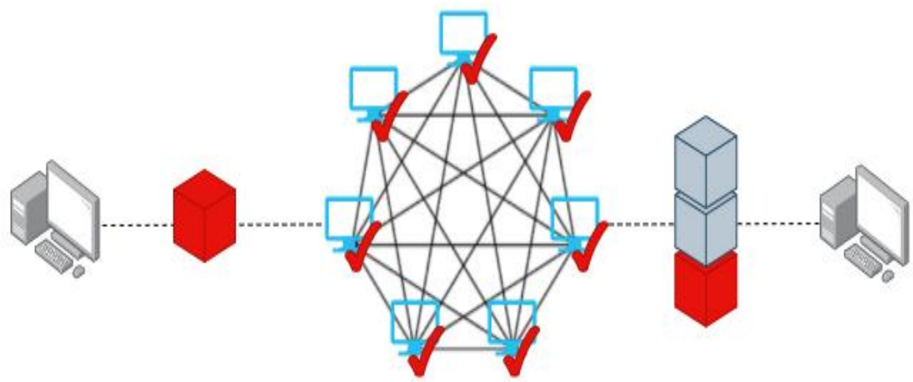

Fig. 29. Clarification of the overall blockchain process [197].

5.4.1 Peer-Peer Distributed Network

Blockchain works on peer-to-peer distributed networks, which make the transactions decentralized and more secure [20]. According to [200], data transmission in the blockchain is generally a copying process, which means copying from one place to another. In this way, the system increases its security and robustness. For instance, copying the digital coin from one wallet to another in cryptocurrency ensures that the coin cannot be double-spent [200]. Fig. 30 illustrates the difference between centralized transaction systems and distributed transaction systems.

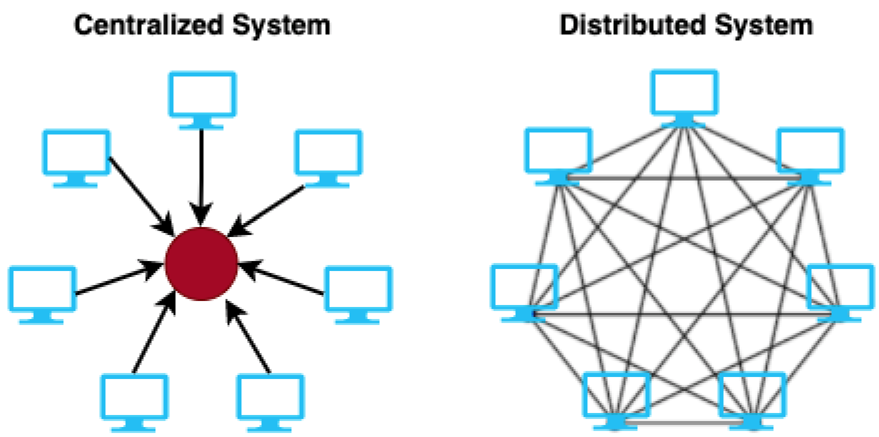

Fig. 30. Illustration of centralized and distributed transaction systems.

5.4.2 Hash Cryptography

Each block has two hashes in the blockchain: one for the block itself and another for the previous block [20]. Generally, a hash is a function that converts any text to fixed-size text [205]. The hash function is an essential part of blockchain systems. Hash functions and public-key cryptography are critical in securing any system, which means they are key players in blockchain systems. The cryptographic hash is a mathematical algorithm, sometimes known as a one-way function (e.g., a series of 256 bits) [197]. There are several types of cryptographic hashes, but they need to meet the following requirements: be one-way, deterministic, compute rapidly, demonstrate the avalanche effect, and withstand collision [196]. For example, the SHA 256 bit cryptographic hash is the most popular [196]. The SHA 256 stands for Secure Hash Algorithm with 256 bits of memory, developed by the United States National Security Agency [196]

5.4.3 Immutable Ledger

Generally, there are two ledger objectives: immunizing all transactions and providing all the transactions for blockchain users [19]. Ponteves et al. [196] discussed the difference between a traditional ledger and the blockchain. A traditional ledger is usually stored in one place, and changing data in it does not affect the rest of the data. In contrast, the blockchain is digital, decentralized, and distributed [206]. Thus, it is extremely difficult to change a single block in the blockchain without affecting the rest of the blockchain. Consequently, it provides an immutable ledger.

5.4.4 Mining

Mining is the process of making new blocks [200, 19]. According to [196], mining involves finding the golden nonce (number used once), which gives the system extra control and fixability. The nonce can manipulate the "hash" value until obtaining the correct hash number that is below the blockchain target. When the miner finds the golden nonce, the block can be added to the blockchain.

5.5 Smart Contracts

Blockchain systems perform based on computer programs run by miners, known as smart contracts [19]. Therefore, smart contracts play a significant role in maintaining the complexity of the blockchain network. For example, Ethereum and Hyperledger Fabric have blockchain-based smart contract systems that maintain the complex distribution, unlike Bitcoin [19].

5.6 Blockchain Layers

[205, 19] presented the different layers of blockchain. Fig. 31 is a combination of their analyses. The layers begin with the application layer and descend to the hardware layer. Generally, each layer has its responsibility. For instance, the main role of the application layer is the user interface and apps, which provide a user with a way to interact with systems. This layer has issues, such as host security and privacy, malicious codes, and several others [205]. Fig. 31 illustrates the responsibilities of each layer. This section focuses on the network, consensus, and incentives layers.

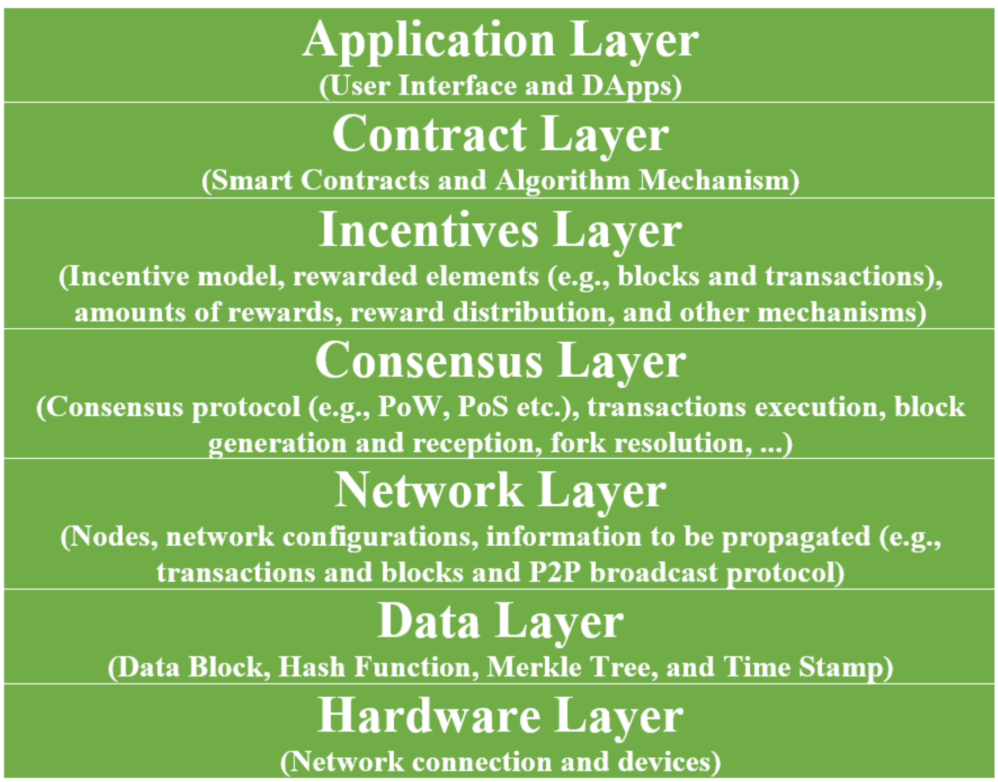

Fig. 31. Blockchain layers.

5.6.1 Network Layer

Establishing authenticity; node interactions; and discovering nodes, transactions, and blocks are network layer responsibilities. Consequently, this layer is known as the backbone or the center of the blockchain architecture [205]. Nodes and the broadcast protocol are the main parts of the network layer [19]. In the blockchain, nodes create and send transactions. Nodes also use consensus algorithms to insert a recent block into the blockchain and execute transactions, hence, they play a significant role in maintaining the state of the blockchain. The main role of the broadcast protocol part is to manage the information propagating in the blockchain network [19].

5.6.2 Consensus Layer

The consensus layer in the blockchain is the layer that deals with consensus protocols. The consensus protocol (a.k.a. consensus mechanism) is a cohort mechanism that works with distributed decentralized networks to achieve unanimous agreement. Each consensus protocol has its own way to reach a level of agreement. There are several types of consensus algorithms such as PoW, PoS, PoA, and PoET [205].

5.6.3 Incentives Layer

In the blockchain, the incentive layer primarily inspires participants to contribute to the blockchain's data-validating processes by distributing rewards [205]. The blockchain system's rewards are block rewards and transaction fees. The block reward is given for generating blocks and transaction fees for completing transactions [19].

5.7 Smart Cities and Blockchain Technology (The Blockchain City)

Nowadays, the design of cities focuses primarily on environmental aspects without considering community engagement, leading to low trust in government [17]. Smart cities had begun to adopt blockchain technology until the concept of the blockchain city appeared in 2018 [18]. Smart city scholars illustrated the significant implications of blockchain for individuals, which improve security, trust, and civic participation [17]. The second generation of blockchain emerged due to the complexity of the distributed tasks underlying cryptocurrencies [19]. Blockchain technology in the smart city domain has a comprehensive revolutionary role in improving the security, efficiency, flexibility, and transparency of public services [17]. This section covers the role of blockchain in various smart city domains and challenges.

As previously stated, technology plays an important role in increasing a city's smartness level. For example, blockchain technology dramatically impacts the transitions between stakeholders in the smart city domain concerning security and privacy, which are the main smart city challenges. Thus, the level of city smartness increases [207]. Treiblmaier et al. [207] discussed blockchain as a primary driver for the smart city. They specified nine smart city dimensions that can benefit from blockchain technology: healthcare, logistics, mobility, energy, governance, industrial, home, and education.

For instance, blockchain technology plays a significant role in increasing healthcare service speed, data security, and accessibility and reducing cost [17]. Consequently, blockchain technology has recently gained the attention of researchers [20, 208]. Hussien et al. presented an analytic review of blockchain use in healthcare applications [20]. They used ScienceDirect, IEEE, and Web of Science as their main databases. In addition, they specified “blockchain,” “healthcare,” and “electronic health records” as the main research keywords.

One of the main electronic health record (EHR) challenges is that the records are in an information repository, which is usually central and thus becomes a single point of failure [20]. By applying blockchain technology in the healthcare sector, the health and prevention of diseases will be enhanced due to the blockchain’s effectiveness in improving the health system’s performance [208]. Alonso et al. [208] presented the percentages of relevant health topics that included blockchain, and the results of their study are presented in Fig. 32.

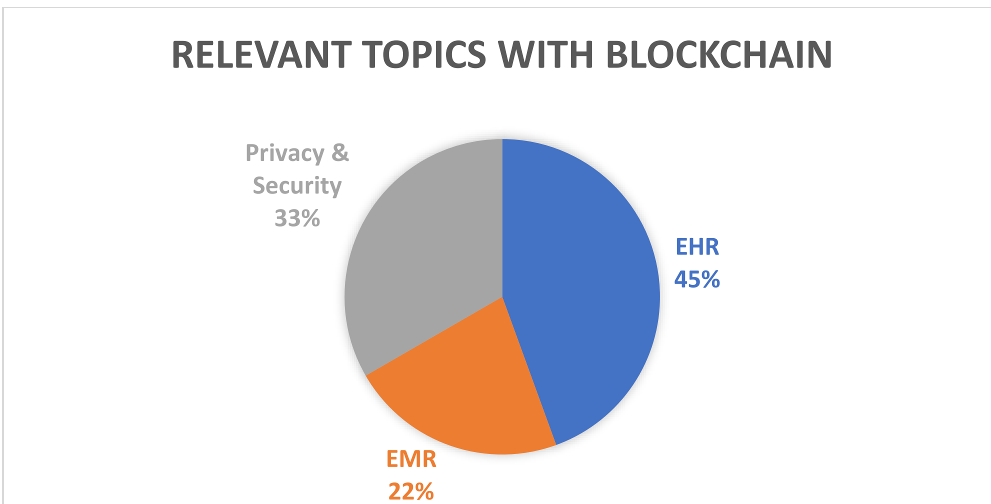

Fig. 32. Percentages of topics related to the blockchain in e-Health.

In terms of security and privacy, there is no doubt that smart cities face tremendous management, privacy, and security challenges. For that reason, blockchain technology has attracted the attention of smart city scholars. However, the difference between privacy and security is misleading. Nowadays, our lives are becoming more manageable. Nonetheless, our privacy issues have become more critical and riskier. There is a similarity between privacy and security problems. Privacy and security work together: if the security is not effective, there is no privacy [209]. By using information security, we can identify the sensitivity of the data and where and how to use security controls [209].

Blockchain technology is becoming more popular because of the financial sector. Some companies utilize the blockchain to develop solutions for those who cannot use banks [17]. Cryptocurrency has recently changed the financial world. For example, several cryptocurrencies are based on blockchain technology, such as Bitcoin, Ethereum, Zcash, and others.

Administrators also consider smart city management or governance to be a key challenge. As mentioned in the smart city chapter, governance in smart cities consists of several sectors. For example, in governance energy (energy grids), there are several kinds of energy grids, such as the Brooklyn Microgrid (BMG), which is a peer-to-peer energy system [17]. There are various benefits of applying blockchain technology in the energy sector, such as trading waste solar energy to neighbors, power effectiveness and conservation, and no need for a trusted third party. Blockchain technology has a significant impact on improving city operations. The blockchain promises to enhance city services, structures, and efficiency and trust, while reducing time and cost. There are several examples of collaborations between blockchain innovators and the government. [210] illustrated the benefits of the blockchain for the business of the U.S. government.

Finally, blockchain plays an innovative role in the mobility sector by supporting negotiations and transferring money between car owners and also paying for tolls and fuel without a trusted third party [17]. All these sectors are smart city dimensions, thus, demonstrating the power of applying blockchain in a smart city setting.

5.8 Blockchain Challenges

Emerging technology such as blockchain technology faces several challenges that are slowing its adoption process. Sharma [22] discussed five primary challenges for blockchain adoption in 2020: scalability, energy, time, interoperability, and a lack of talent and standardization [22]. This section focuses on scalability and energy consumption due to their relevance to the dissertation work.

5.8.1 Performance and Scalability

Performance and scalability represent significant challenges for blockchain. We address them in one section because of their strong effect on each other. The founder of Ethereum, Vitalik Buterin, proposed the scalability trilemma [211, 212]. The scalability trilemma in blockchain illustrates the trade-off between decentralization, security, and scalability, as shown in Fig. 33. Each one of these properties plays an important role in blockchain technology. This framework is also useful for comparing blockchains systems and models. Thus, achieving a satisficing level of decentralization, scalability, and security is a crucial challenge for blockchain technology.

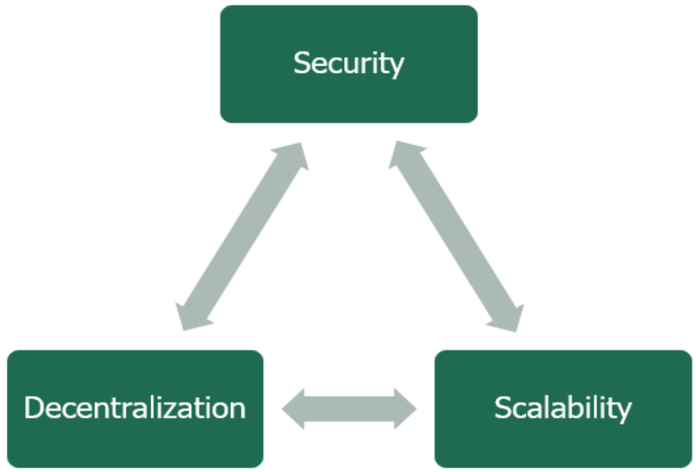

Fig. 33. The scalability trilemma in blockchain.

Security, scalability, and decentralization are blockchain properties that significantly enhance the blockchain's value proposition [211]. Hafid et al. [212] addressed security as an inevitable aspect, scalability as a challenge, and decentralization as the nature of the blockchain. In the blockchain, decentralization refers to the degrees of all the ownership, influence, and value in the blockchain [211]. This section discusses the scalability challenge in blockchain systems.

According to [212], healthcare, cryptocurrencies, government, IoT, AI, and other sectors have decentralized, immutable, and distributed peer-to-peer networks as a result of blockchain technology despite the scalability limitations that blockchain faces [212]. However, the authors describe blockchain scalability as challenging and provide solutions to this challenge. They classified scalability solutions into two layers. In the first layer, solutions modify the blockchain. Conversely, the second layer solutions do not, which means they occur outside the blockchain.

The first-layer solutions may change the blockchain structure such as block size. Sharding, SegWit, Big Block, Stellar, and DAG) are first-layer solutions [212]. Payment channels and side chains are some of the second layer solutions [212]. Decomposing the network into subsets is the most promising solution for the blockchain scalability problem, which is known as the sharding solution [212]. The sharding (a.k.a. clustering) solution can be considered within the first or second layer. We use the nearly decomposed term in our work, which the complexity chapter explains in detail. The results of the sharding process are called shards, subsystems, or committees [212, 25]. Fig. 34 briefly illustrates the analysis conducted by [212].

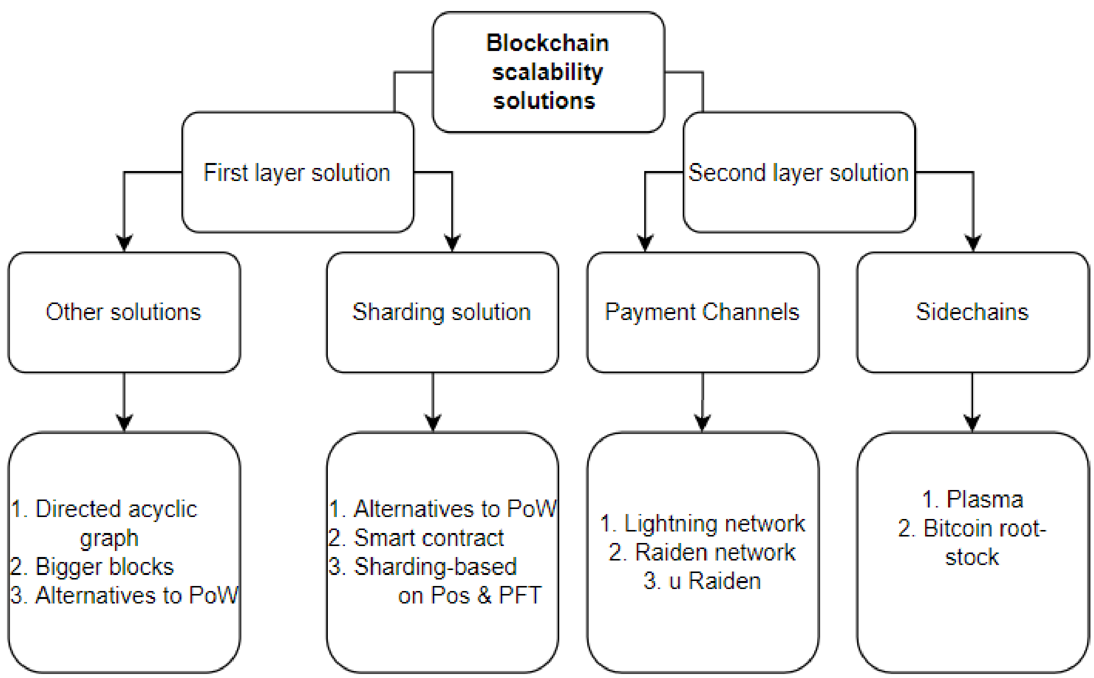

Fig. 34. The blockchain scalability solutions taxonomy.

Clustering and clustering techniques are popular in wireless sensor networks (WSN) and mobile ad hoc networks (MANET). Some of these techniques are suitable for sharding the blockchain. Generally, the clustering technique consists of grouping nodes into groups known as clusters, committees, or subsystems [213]. These clustering techniques drive several objectives, such as optimizing resource consumption, network load balancing, and others [213]. Furthermore, these techniques play a significant role in selecting cluster heads (CHs), which are the full nodes in the blockchain. Selection of the CHs can use centralized or distributed selection approaches. Researchers have studied clustering from different perspectives: energy consumption, heterogeneity, and mobility [213].

Topology management is a primary blockchain network challenge. Topology management is a popular challenge in ad hoc networks, WSN, CPS, and IoT networks [213]. Topology management contains several techniques, of which clustering is one, thereby grouping nodes into groups. In this way, the systems will be more efficient, manageable, and fair [213]. The clustering process consists of two steps: grouping nodes and assigning responsibilities [213].

Shahraki et al. and Nguyen et al. [213, 214] proposed and discussed several clustering techniques that can be used on the blockchain. These techniques are based on data transmission, time, and event. In the data transmission technique, the clustering process is based on the data transmission rate. However, in the time-based method, the clustering process starts at a certain time and restarts again if the network reaches the predetermined load. In the event-based method, the clustering process targets an event such as bandwidth consumption. Shahraki et al. [213] refer to scalability as an intricate challenge due to the vast number of nodes and communication overhead, which clustering can solve.

The main step of the clustering process is the selection of the CHs. In the blockchain network, CHs are full nodes. There are several approaches to selecting CHs in the network. The selection approaches are based on several criteria: neighbors, energy, and distance. Thus, the three most popular selection techniques are lowest ID, highest degree, and low energy adaptive clustering hierarchy [215]. A number of clustering techniques exist such as K-means, Sailfish Optimizer, Grey Wolf optimization, genetic algorithm, Hybrid K-means, Ant Lion optimization, particle swarm optimization, and random [216]. However, we propose using LAP as a way of selecting CHs and as a clustering technique.

5.8.2 Energy

The blockchain consumes vast amounts of energy because of the hash calculations, mining, and no intermediary's participation [200]. Therefore, researchers are studying blockchain from the energy point of view. Usually, reducing energy consumption plays a role in affecting the efficacy and decentralization levels, which means there is a trade-off between energy, performance, and decentralization.

Nair et al. [200] addressed several methods that consume energy in blockchain and proposed ways to reduce it during transactions. Some of their approaches to minimizing the energy losses are specializing in the data center, resource-efficient mining, transfer of proofs, sawtooth blockchain software, and side chains. For example, specializing in the data center aims to improve the whole cost of ownership. In contrast, the main purpose of the resource-efficient mining approach is to reduce the energy consumption in the blockchain by using SGX (Software Guard Extension), which is trusted hardware by Intel.

With regard to the sawtooth blockchain software, Intel proposed Hyperledger, which randomly chooses a user to write a block based on PoET. Finally, there is the side chains method that uses the PoA, which means selected nodes (nodes that have accessibility permission) run the network [200].

5.9 Summary

Some organizations rely on centralized banks, where a third trusted party is needed. The centralized structure has security, reliability, and performance issues [19], hence, blockchain technology emerged. Recently, organizations and systems have begun adopting blockchain, which reduces centralization and increases security and accessibility [20]. However, blockchain technology faces many challenges, hence, three types of blockchains have been developed from a network perspective: permissionless, permissioned, and consortium blockchains (hybrid). The latter result from the integration of public and private blockchains. Several researchers consider it to be a private blockchain, while others consider it differs from private blockchains [20]. The blockchain chapter addresses all the aspects essential to understanding blockchain technology.

Some smart city models do not consider community engagement, which leads to low trust in government [17]. Thus, smart city domains have begun adopting blockchain, with the term “blockchain city” appearing in 2018 [18]. Blockchain in the smart city domain has a significant role in improving public services, security, efficiency, flexibility, and transparency [17]. It also impacts on the speed of transitions between smart city stakeholders and minimizes security and privacy issues, which are the main smart city challenges. Consequently, blockchain use leads to an incremental rise in the level of city smartness [207].

Smart city researchers identified nine smart city dimensions that can utilize blockchain technology: healthcare, logistics, mobility, energy, governance, industrial, home, and education [207]. For instance, blockchain has a significant impact on healthcare systems. It has a key role in increasing the speed of healthcare services, especially in data security, accessibility, and reducing costs [20, 208]. One healthcare challenge is the EHR, which are generally centralized [20]. A centralized EHR system means a single point of failure, which is an issue that the blockchain solves perfectly.

Unfortunately, the blockchain also has its challenges. There are five main challenges in the blockchain domain: scalability, energy, time, interoperability, and a lack of talent and standardization [22]. This chapter focuses on scalability and energy consumption due to their relevance to the dissertation work. On the scalability side, Vitalik Buterin proposed the scalability trilemma [211, 212], which illustrates the trade-off between decentralization, security, and scalability. There are several proposed solutions for scalability challenges in the blockchain. [212] provided a review of the solutions proposed for this challenge. They identified two layers of scalability solutions, which are solutions that modify the blockchain (e.g., sharding, SegWit, Big Block, Stellar, and DAG), and solutions that occur outside the blockchain (e.g., payment channels and side chains) [212].

Blockchain scholars also study blockchain from an energy perspective. Blockchain systems consume extensive energy due to hash calculations, mining, and no intermediary participation [200]. Therefore, scholars have proposed several ways to minimize energy consumption: specializing in the data center, resource-efficient mining, transfer of proof, sawtooth blockchain software, and side chains [200].

CHAPTER 6

A FRAMEWORK FOR DESIGNING BLOCKCHAIN SYSTEMS IN A SMART CITY SETTING

6.1 The Framework

We propose a framework utilizing the PArchitect tool, Conant analysis, and LAP. Each step has a corresponding section that explains how it is used, afore. Fig. 35 clarifies the overall steps of our framework. The context of the smart city context is the principal and first step in modeling. We select the smart city context before beginning the modeling process. The modeling process begins by understanding and analyzing the real-world system's interactions and later developing the model with the information flow perspective of the system. The information flow for the smart city systems step is shown in Fig. 36.

After completing the system's information flow, the data analysis begins to prepare the results. The interpretation of the results for the real world has two outputs: if the model meets the validation criteria, the model development circle is completed. Otherwise by returning to the system's information flow step, we perform adjustments until the model meets the validation measures.

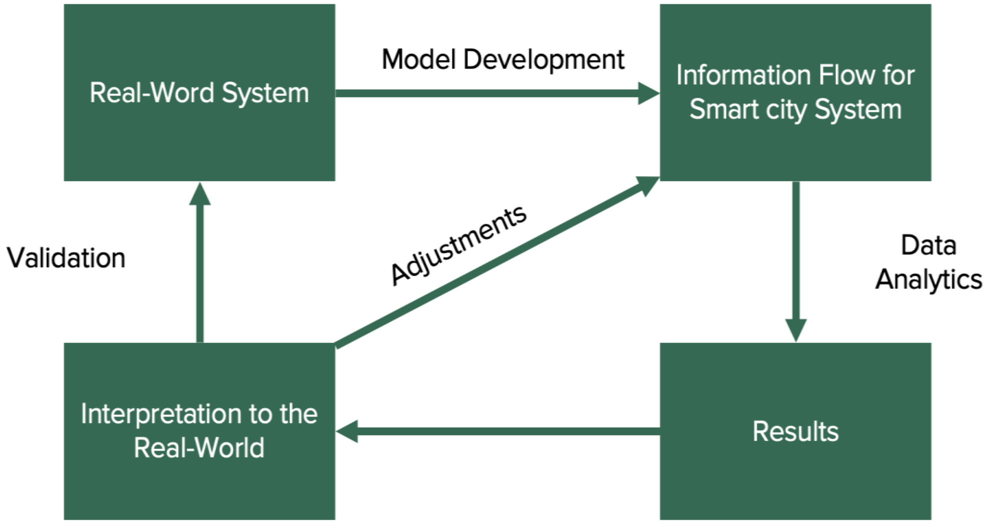

Fig. 35. The modeling framework [218].

The information flow for the smart city system is presented infra in Fig. 36. It has five main steps: observing and describing, PArchitect, Conant analysis, converting a system into a graph, and using MIS as a tool to find LAP. Fig. 36 infra illustrates the theoretical information steps of the framework.

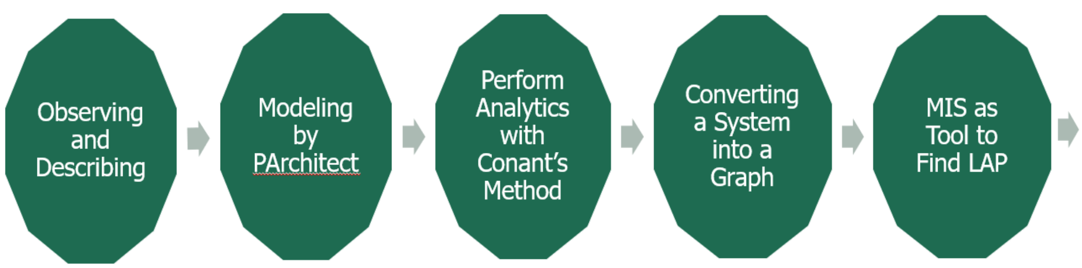

Fig. 36. The information flow for the smart city systems.

The observing and describing step is the key element in creating a universal smart city model because the modeler can choose any context or vision, which the PArchitect tool calls the “final value.” There is a shortage of smart city modeling, and the PArchitect modeling step solves this shortage. The modeling chapter illustrates the PArchitect modeling technique. This step plays a significant role in understanding the systems from the selected contextual point of view and collecting the necessary data. The Conant analysis begins after the modeler has obtained and understands all the information needed for the system.

The process of selecting who will be acting as full nodes on the blockchain system and defending the subsystem in this framework is the result provided by the Conant analysis. After modeling the system, we will propose an innovative blockchain model by applying LAP. The LAP will be based on the Conant analysis result. The LAP has a key role in distributing the full nodes in blockchain systems or the CHs in any known system. Additionally, it plays a significant role in clustering blockchain systems.

6.2 Case Study Introduction

Undoubtedly, blockchain technology plays a significant role in improving all smart city dimensions. We use healthcare as an example to illustrate the advantage of using blockchain technology. We use the health sector as a case study for many reasons. The healthcare system involves a variety of technologies, tasks, people, and complexity levels. Smart healthcare is also one of the main dimensions considered in smart cities.

An individual patient’s data is estimated at USD seven thousand annually. This is the estimation derived from a blockchain company known as Timi Inc. [199]. For that reason, many healthcare companies are focusing on blockchain technology. For example, with the aim of giving patients accessibility to their own EHRs [199].

However, blockchain technology is an ideal solution for systems that must be decentralized, and not all systems need to be decentralized [20]. The healthcare domain is one of the most significant domains to potentially benefit from blockchain technology [23]. Hussien et al. [20] proposed an evaluation of blockchain technology to ascertain whether blockchain technology is essential in healthcare systems. They divided their framework into three sections: data collection and exchange, transformation, and storage and access. They addressed several advantages of using blockchain: security, privacy, trusted environment, transparency, tamper-proof, medical record tracking, and robustness.

Siegel [23] discussed the Health Insurance Portability and Accountability Act ‘s (HIPAA) view of blockchain technology. Generally, HIPAA provides instructions for healthcare agencies to protect the privacy and security of the client’s health information. According to Siegel’s analysis, blockchain uses mathematical encryption, which HIPAA prohibits because the mathematical encryption conflicts with its privacy rule. The blockchain also faces similar issues with the General Data Protection Regulation (GDPR) [199]. Nonetheless, applying the blockchain in the healthcare system mitigates several issues and risks such as security, inconsistencies, patient record retrieval, and accessibility [23].

Health records are different from cryptocurrency records. For example, health records can be consultations, images, blood and other test results, prescriptions, or surgical procedures, therefore, a trusted entity is needed to validate such data each time it is added [217]. Alder [217] illustrates that the data would be added as a block to the chain after validation, hence, the blockchain represents the patient's entire medical history, making our model a perfect fit for such a task.

6.3 Health Care System

Fidelity, efficiency, and memory significantly impact a decentralized health care system [219]. Shannon discussed these three critical points [95, 32]. Health service delivery becomes distributed, thus, it becomes a complex and uncoordinated network of services [220]. This distribution makes case management an important part of healthcare systems. The case manager plays a significant role in smoothing out the sequence of services in the health care system.

Case management is a useful technique to apply in the smart city domain. It can be useful in any domain requiring service management, such as the health care domain. That being said, the case study aims at the healthcare dimension of the smart city. Most healthcare systems are centralized, where the clients do not have full control of their data. Unfortunately, clients still need to contact the case manager or the health provider to obtain their health data or send it elsewhere. Researchers have proposed several ways to solve this issue, and blockchain is one of them.

Dimitrov [199] presented a review about the potential use of blockchain technology in the healthcare system. He elucidated three main areas for utilizing the blockchain in a healthcare system: storing medical records, patient data ownership, and patient outreach. As previously mentioned, healthcare systems have their own rules regarding patient security and privacy (e.g., HIPAA and GDPR). For this reason, a public blockchain is not a good fit. However, a private blockchain can effectively perform the task [199].

The case study used in this work is the Community Justice Programs (CJP), formerly Treatment Alternatives for Safer Communities. The CJP is a community corrections system under the guidance of Jefferson County, Alabama. It is a part of the justice program of the University of Alabama at Birmingham's School of Medicine, Department of Psychology and Behavioral Neurobiology [98], who established it in 1994. Through comprehensive case management, the CJP supports people who have addiction recovery and behavioral health disorders and become involved in the justice system due to those problems [221].

6.3.1 Health Monitoring System – PArchitect

The generalized model of the health monitoring system is created using the PArchitect tool. The tool is based on a value-driven model, as explained in Chapter 3. The model assumes a hierarchical tree structure. The model's main focus is communication in treatment processes in the CJP. Hence, we selected the drug-testing process. The drug-testing process involves several steps: capturing the client, assigning a color, calling a messaging service, going to the testing site, checking in, testing, reporting test results, and treatment and assessment.

The model presents the drug-testing process, which is a part of the CJP system. The model starts from the top of the tree. In this way, any appropriate value can be modeled. This model tracks a value associated with the client's data generation, transmission, and storage. Therefore, the initial value is described as "client's data records."

Fig. 37 illustrates the highest level of the system representation using PArchitect. The health monitoring system is the oval central object, representing all the value exchanges occurring in the system. “Initial Client Value” identifies the state of the initial value on the left side of the health monitoring system. On the right side of the system is the “Final Client Value.” The final value determines whether the client requires “no involvement in the justice system” or “further involvement in the justice system.” All these instructions obey the “Reference” located above the health monitoring system.

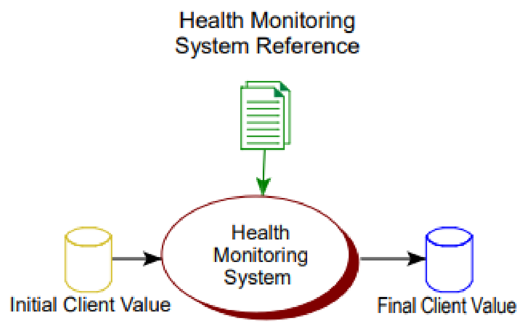

Fig. 37. Highest level representation of the system.

Fig. 38 represents the health monitoring system from the client’s perspective. The capturing, treatment and assessment, and maximum improvement decision transitions are the three main transitions of the model. Generally, the capturing transition represents the process of bringing the client into the health monitoring system, the treatment and assessment transition represents treatment plans and tasks, and the maximum improvement decision transition represents the client discharge decision.

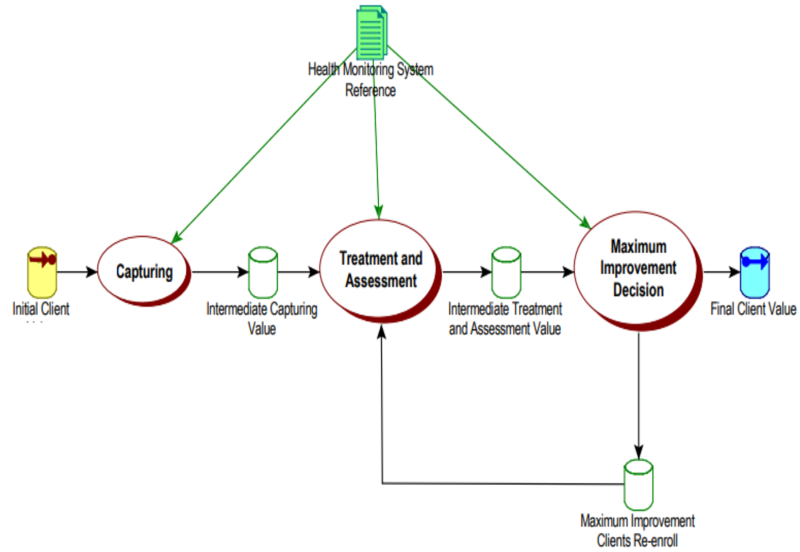

Fig. 38. Decompressed model of the health monitoring system.

All three transitions are decompressed and modeled to provide more detail. Fig. 39 explains the capturing process in the health monitoring system. The capturing transition is a compressed transition that contains two transitions. The first captures a compressed transition, as shown in Fig. 39. The initial capturing value results from that compressed transition, which is explained in Fig. 40. Following this, the filter transition occurs, and the case manager and health monitoring system reference direct this process.

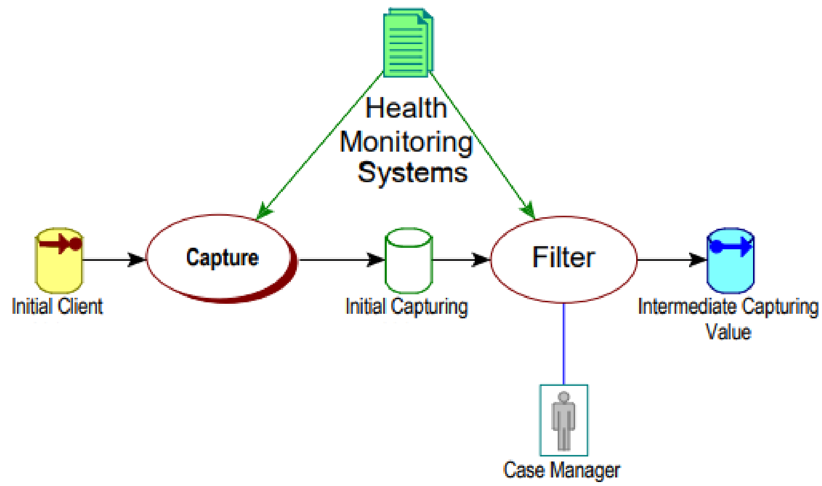

Fig. 39. Decompressed model of the capturing transition.

Fig. 40 explains the capture process in the health monitoring system, which is a compressed transition. As previously mentioned, if the clients (health monitoring system participants) have drug felonies, they will be given a court order to complete the CJP treatment. The client capture transition represents this process in Fig. 40. There are two results based on the capturing process: “enroll” and “dismiss.” The “case transition,” processes these two results, as shown in Fig. 40. Then, the judge and the case manager make a decision based on the case enrollment and dismissal references. The initial capturing value is the main result of this phase, which feeds the filter transition shown in Fig. 39.

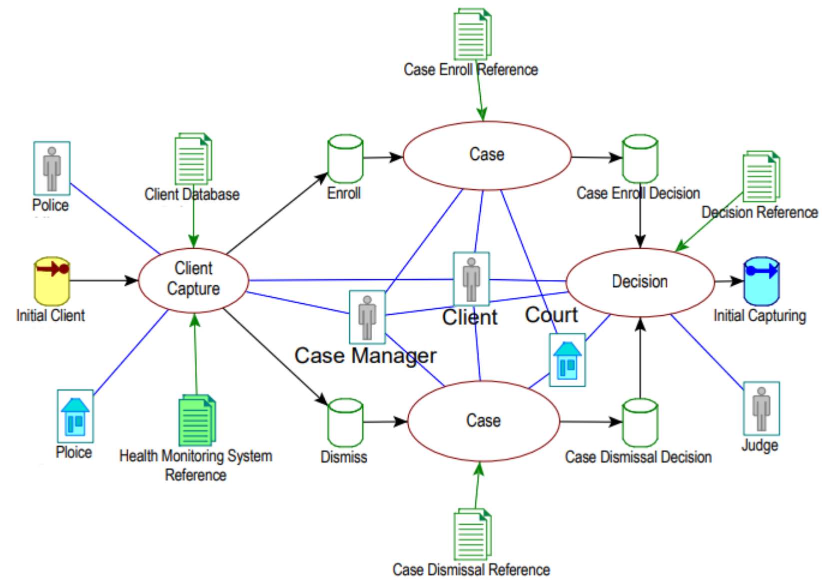

Fig. 40. Decompressed model of the capture transition.

Fig. 41 explains the treatment and assessment transition in the health monitoring system, represented as a decompressed transition in Fig. 38. This decompressed transition is the heart of this process. It contains two compressed transitions: assessment and plan and treatment tasks.

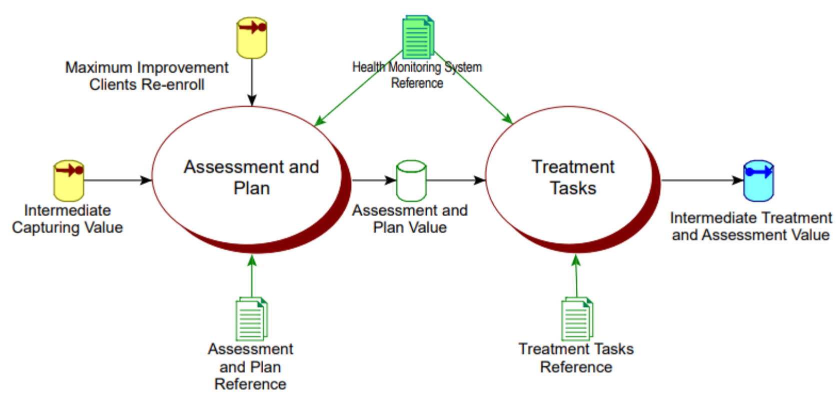

Fig. 41. The treatment and assessment transition.

The assessment and plan transition, presented in Fig. 42, represents the client's needs and directions to complete the program. It has one compressed transition and two transitions: application, comprehensive screening and assessment, and plan.

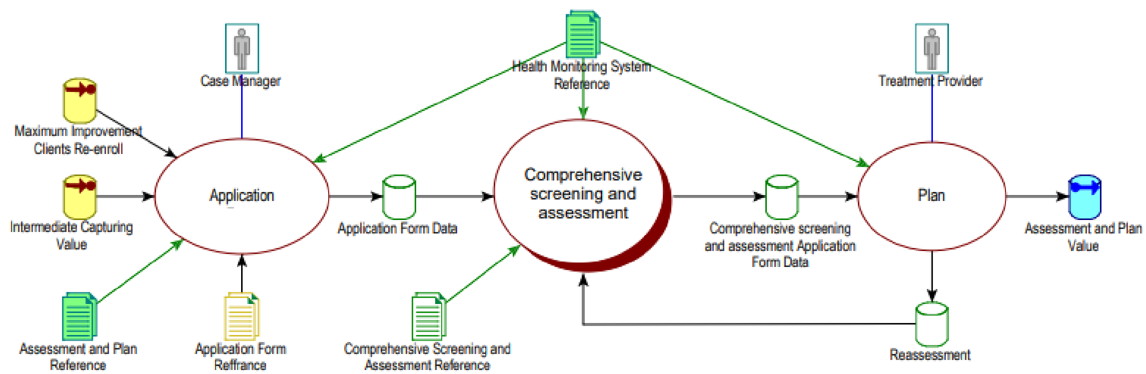

Fig. 42. The assessment and plan transition.

Fig. 43 represents a decompressed comprehensive screening and assessment transition, which contains four significant transitions. The transitions begin with general client information, which the case manager requests based on the general information reference. Then, the client's medical information follows that meets the medical information reference, followed by the client's criminal history. Based on this information, the case manager can make the assessment. The result of this phase is the input for the plan transition, as shown in Fig. 42.

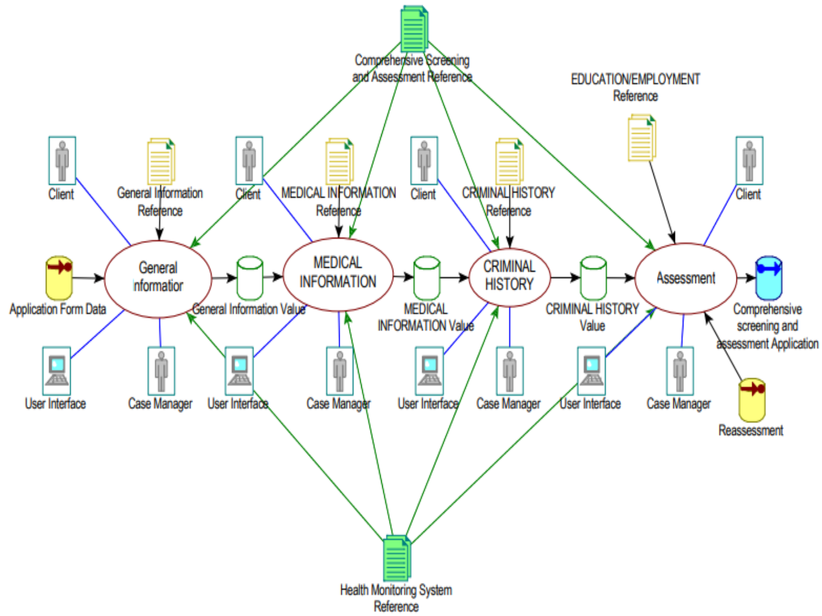

Fig. 43. The comprehensive screening and assessment transition.

Fig. 44 represents a decompressed model of the treatment tasks transition, including linking to services, attend plan requirements, and intermediate treatment decisions. The linking to services transition requires the case manager to flow the assessment and plan value represented in Fig. 41 infra to link the client to treatments and plan requirements. There are also two compressed transitions: attend plan requirements and intermediate treatment decisions. The intermediate treatment decision is modeled but not presented here because there is no communication between the CJP parties.

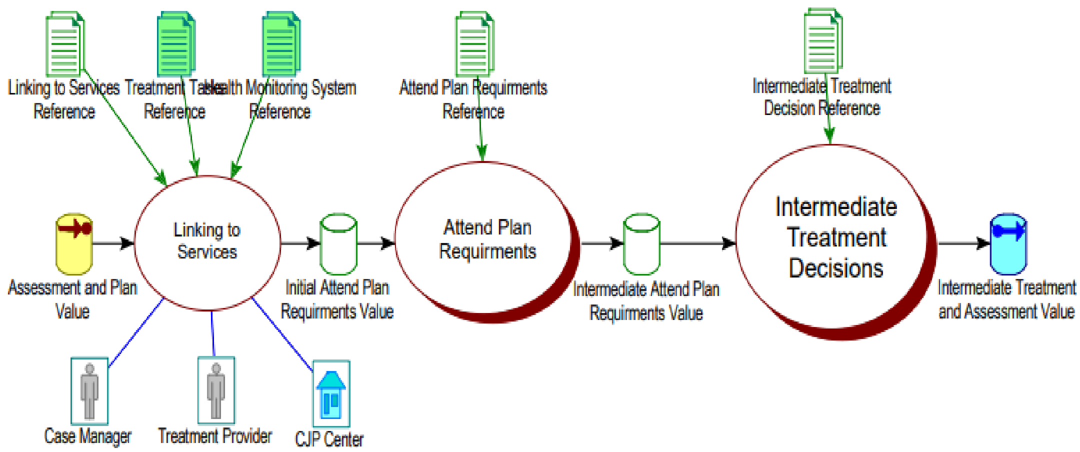

Fig. 44. The treatment tasks transition.

The attend plan requirements transition is decompressed in Fig. 45 and represents the client's engagement with treatment and requirements, which is the main part of the health monitoring system. It includes community service, attending treatment, payment, court hearings, and regular case management calls. The attend treatment transition is the only compressed transition in Fig. 45. The results collection transition collects all these transition results.

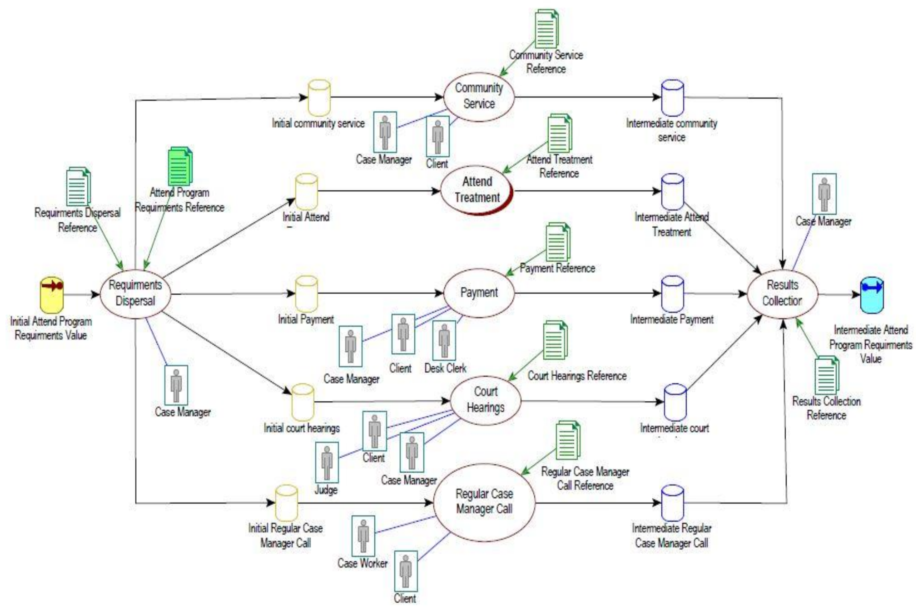

Fig. 45. The attend plan requirements transition.

The “attend treatment” transition is decompressed in Fig. 46 below. It represents generalized health monitoring systems, and identifies four compressed transitions: the client’s actions to finalize a treatment appointment are “appointment process,” the client deciding to attend the treatment appointment or not are “client action,” the client presenting for treatment and other tasks are “registration process,” and the client receiving treatment is “treatment.”

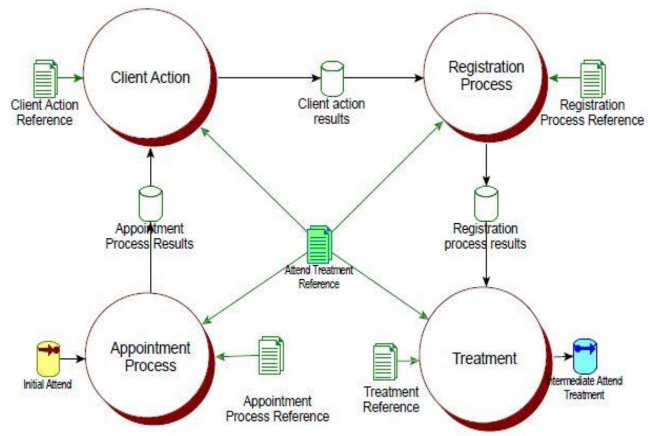

Fig. 46. The attend treatment transition.

Fig. 47 represents a decompressed model of the appointment process transition, which includes the matching process and the results. The appointment considers the comprehensive screening and assessment transition output. As previously mentioned, each client matches a specific standard based on applying the matching process references for the comprehensive screening and assessment output.

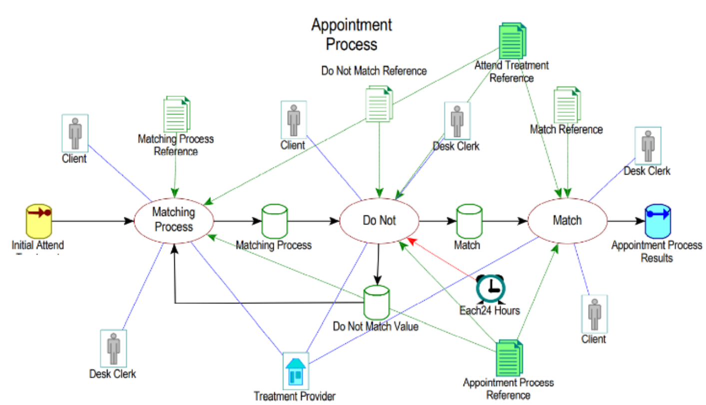

Fig. 47. The appointment process transition.

Fig. 48 represents a decompressed model of the client action transition, which includes two options for the client's actions. After the comprehensive screening and assessment, and appointment processes, the clients who match the standards enroll in the CJP program. Fig. 48 illustrates the first phase after enrolling, which keeps track of the client's attendance and progress. Fig. 48 presents two scenarios for client actions. The case manager, supervisor, and clients should follow the client action reference and the CJP references.

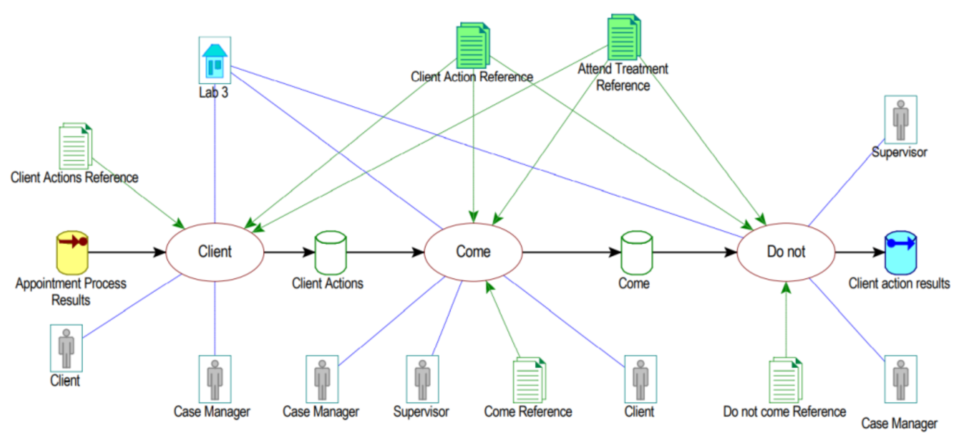

Fig. 48. The client action transition.

Fig. 49 below represents a decompressed model of the registration process transition, which includes three transitions: ID, notification, and payment. Fig. 49 illustrates the first registration and payment phase after enrolling. Fig. 48 illustrates three steps that all clients should perform in this registration process. First, the case manager, desk clerk, and clients should follow the registration process reference, notification process reference, and other references, as shown in Fig. 49. All clients must do so in order to complete the CJP program. The clients can then go to the lab to submit their drug test samples after the registration process.

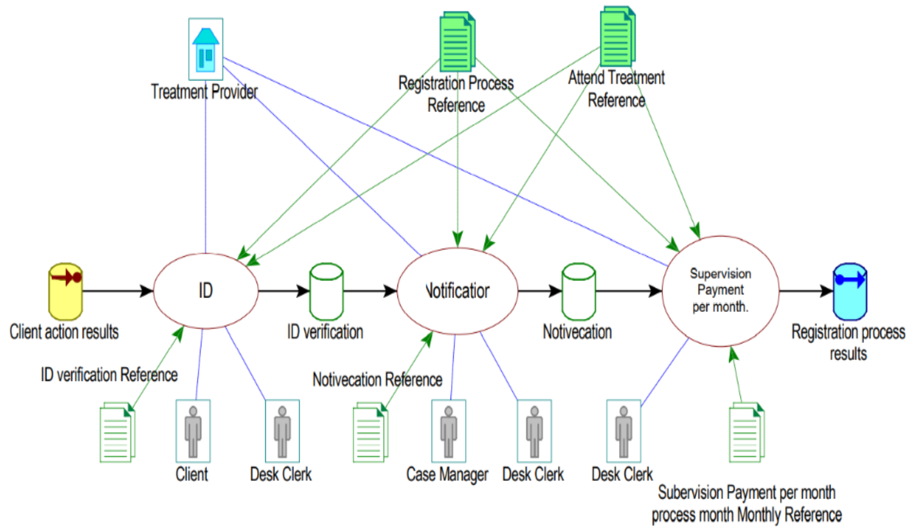

Fig. 49. The registration process transition.

Fig. 50 represents a decompressed model of the treatment transition, which includes three transitions: ID verification, therapeutic treatment, and reject and report to the supervisor. First, the client needs to provide some ID to enter the lab and submit the drug test sample. The client needs to immediately verify their ID prior to treatment or giving test samples. Following this, analysis of the drug test sample begins. If the drug test sample is rejected, the client is reported to the supervisor, and the process represented as “reject and report to supervisor” transition. The therapeutic treatment transition represents a treatment service, including giving a sample, testing the sample, and reporting the results to the CJP system. This result will affect whether the client continues treatment.

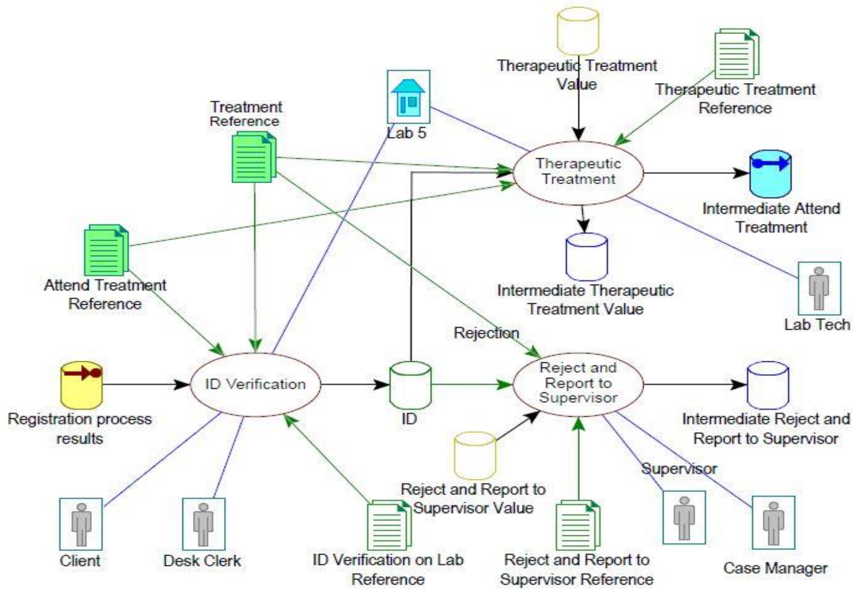

Fig. 50. The treatment transition.

Fig. 38 infra represented the maximum improvement decision transition. Fig. 51 represents a decompressed model of the maximum improvement decision that includes only one transition: the maximum improvement court decision. In this transition, the client meets with the case manager, the judge, and the supervisor at the court to discuss the client's result. The judge oversees the client's involvement based on the client's value. In addition, the client, case manager, and supervisor play a significant role in providing the judge with a clear picture of the client.

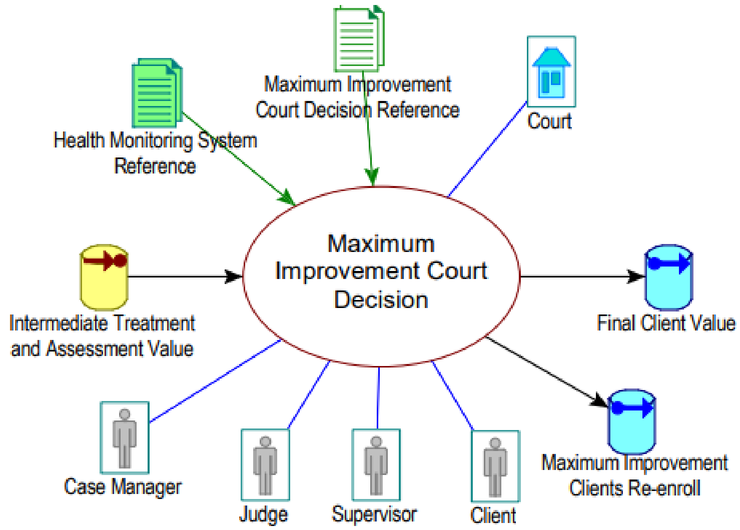

Fig. 51. The maximum improvement decision transition.

For the purposes of the CJP case study, we tracked the client's data records from the "involvement in the justice system," which is the initial client value, to the final value, the "no involvement or reinvolvement in the justice system." As a result, all the parties involved in CJP are captured. Fig. 52 below illustrates the parties' communication in each step of the CJP. Some of these communications have no relationship to the client's health data records. Table XIII presents the communication attempted for each party, which is important for the Conant step.

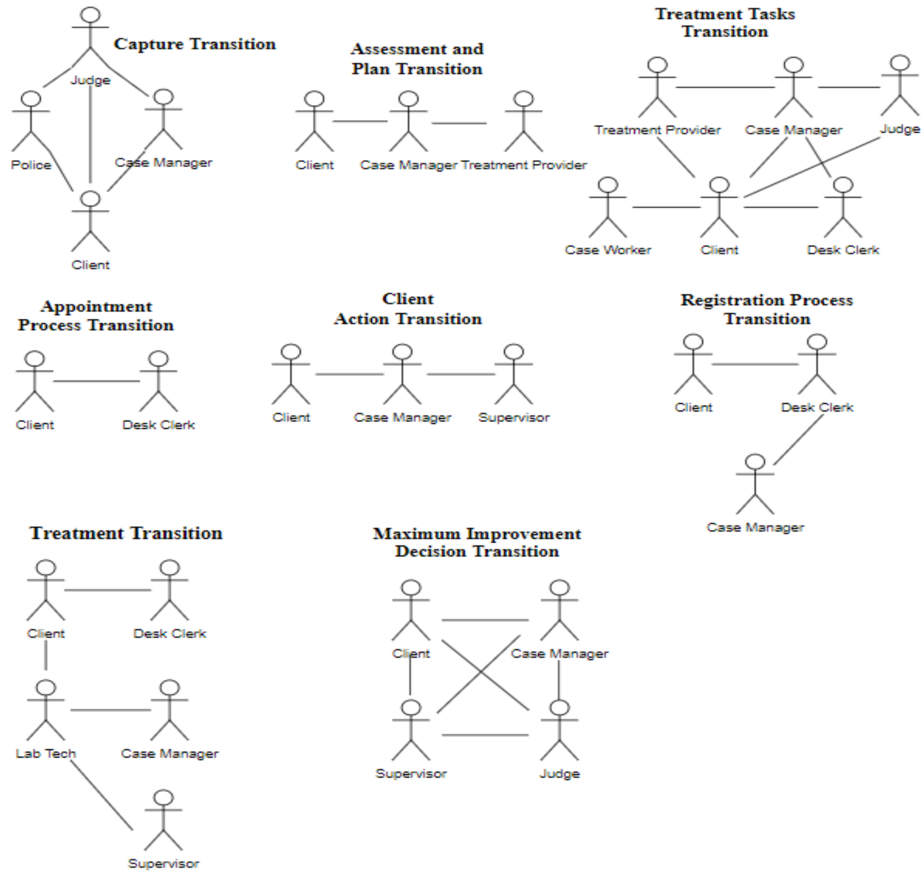

Fig. 52. The CJP parties' communication.

TABLE XIII

COMMUNICATION ATTEMPTS FOR EACH PARTY

Entity \ Time	1	2	3	4	5	6	7	8
Lab Tech	0	0	0	0	0	0	2	0
Case Manager	2	2	4	0	2	1	1	3
Treatment Provider	0	1	2	0	0	0	0	0
Supervisor	0	0	0	0	1	0	1	3
Judge	3	0	2	0	0	0	0	3
Police	2	0	0	0	0	0	0	0
Desk Clerk	0	0	2	1	0	2	0	0
Case Worker	0	0	1	0	0	0	0	0
Client	3	1	5	1	1	1	2	3

Based on analyzing Fig. 52 and Table XIII, the overall CJP parties' communication from the health monitoring system's perspective is presented in Fig. 53. This analysis is important for designing blockchain systems for the CJP. We plan to make the CJP system decentralized and secure, and blockchain is the best way to accomplish that objective. We considered the private blockchain structure due to the HIPAA instructions. After this step, the model is ready for the flowing steps of the framework. The healthcare monitoring systems LAP section presents further details.

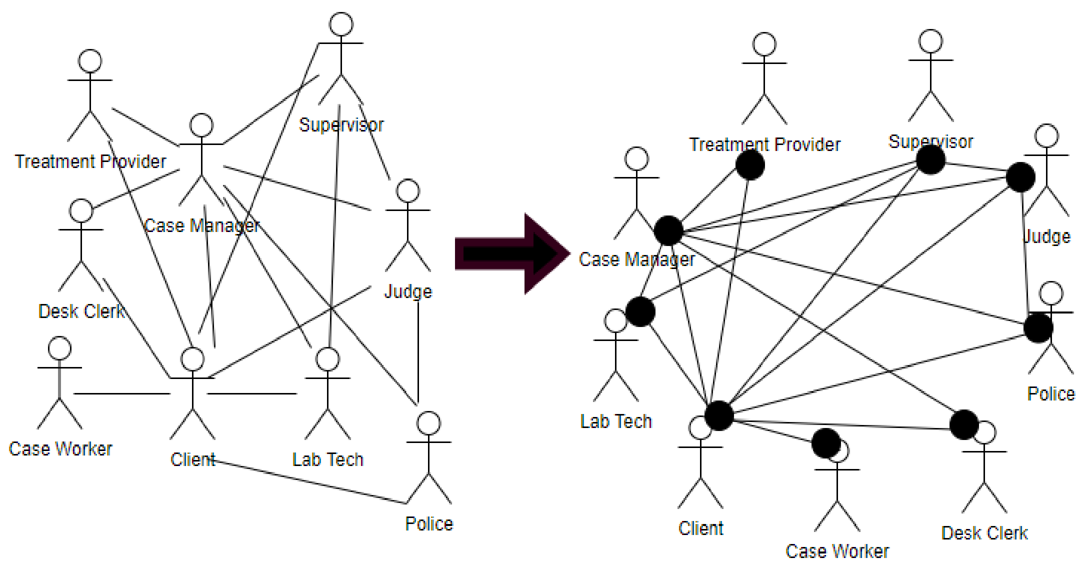

Fig. 53. The overall communication between the CJP parties.

Following this analysis, we ascertained that the case managers have a central role in the performance of the CJP. As a result, we present the system from the case manager's perspective. Thus, we present only the connections that involve the case manager. Fig. 54 infra presents the information-based model of case manager communication in the healthcare system, including five important nodes: Case Manager, Client, Service Provider, Database, and Specialist. Fig. 54 illustrates the average information exchange from the case manager perspective.

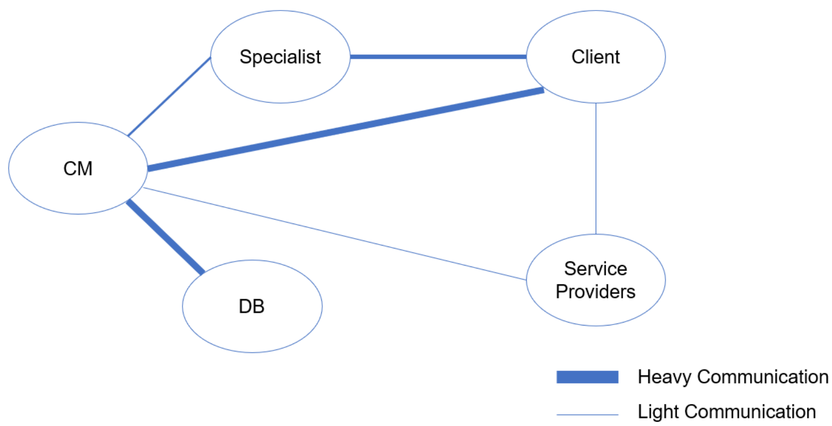

Fig. 54. The CJP communication system from the case manager perspective.

As shown in Fig. 54, clients do not have direct access to the database, and the system is centralized, which leads to substantial communication between the case manager and the client. The case manager also experiences an overload of data and tasks. Based on all the analyses in the PArchitect section, blockchain significantly improves the services, accessibility, and security of systems. Unfortunately, applying blockchain in such a system is unacceptable due to HIPAA security and privacy rules. However, we propose a blockchain model that fits this system well, which Section 6.3.3 explains.

6.3.2 Health Monitoring System – Conant Analysis

In our complex system modeling technique, we need to create subsystems for the complex system. There is an entropy-based technique to nearly decompose a complex system using the estimated number of communication rates for each part. This technique was proposed by Roger C. Conant [25]. Conant's technique reduces the complexity level of the system. Conant nearly decomposes the system based on the communication rate, which means the communication rate in the subsystem should be higher than the rest of the systems [99, 222]. Table XIV illustrates the nomenclature and definitions of Conant's parameters.

TABLE XIV

NOMENCLATURE AND DEFINITIONS OF CONANT'S PARAMETERS [222]

Parameter	**Definition**
K	The number of variables (vectors)
$H(X_j)$	The entropy of the variable S_j
J	The variable index
X_j	A variable vector of observations
X'_j	A variable vector of observations offset by one-time increment later than S_j
N	The number of occurrences of a possible value of S_j
N	Total number of observations
M_j	Upper limit of the range of values of S_j
$T(X_i : X_j{}')$	The transmission parameter
$t(X_i : X'_j)$	The normalized transmission parameter

The PArchitect analysis collects the system's data, processes, key players, and dimensions. These values would be the results if the system performed ideally. The numbers of occurrences for each possible state of the variable are known as entropy. Table XV illustrates the CJP variables, which are grouped into sets of time series observations: lab tech (X1), case manager (X2), treatment provider (X3), supervisor (X4), judge (X5), police (X6), the desk clerk (X7), case worker (X8), and client (X9). These numbers are based on the PArchitect analysis.

TABLE XV

THE INITIAL DATA OF CJP ACTORS' EVENTS

	0	1	2	3	4	5	6	7
X_1	0	0	0	0	0	0	3	0
X_2	2	2	4	0	2	1	1	3
X_3	0	1	2	0	0	0	0	0
X_4	0	0	0	0	1	0	1	3
X_5	3	0	2	0	0	0	0	3
X_6	2	0	0	0	0	0	0	0
X_7	0	0	2	1	0	2	1	0
X_8	0	0	1	0	0	0	0	0
X_9	3	1	5	1	1	1	2	3

Therefore, we begin by finding the entropy of the variable X_j by applying the equation (3.1). We calculate the entropy of the variable X_j, where j ranges from 1 to 9 by using the Wolfram Mathematica code [45]. Fig. 55 below presents the calculation results for individual entropies of nine variables and three counted events for nine distinct variables.

Three Counted Events

	n_1	n_2	n_3
X_1	0	0	1
X_2	2	3	1
X_3	1	1	0
X_4	2	0	1
X_5	0	1	2
X_6	0	1	0
X_7	2	2	0
X_8	1	0	0
X_9	4	1	2

Entropy

H_1	3.
H_2	2.15564
H_3	3.
H_4	2.75
H_5	2.75
H_6	3.
H_7	2.5
H_8	3.
H_9	1.75

Fig. 55. The three counted events and entropy for nine variables.

After calculating the entropy of the variable X_j, we can begin calculating the joint entropy using the (6.1) equation, which is presented in Table XVI. Following this, we calculate the transmission parameter represented in Table XVII. Then we calculate the normalized transmission represented in Table XVIII, using the (6.2) equation.

$$T(X_i\!:\!X'_j) = H(X_i) + H(X'_j) - H(X_i, X'_j) \qquad (6.1)$$

TABLE XVI

THE JOINT ENTROPY CALCULATION RESULTS

H_{X_i,X_j}	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	0.	0.	0.	0.	0.	0.	0.	0.	0.
X_2	0.	2.	1.	1.	1.	0.	0.918296	0.	1.5
X_3	0.	0.	0.	0.	0.	0.	1.	0.	0.
X_4	0.	1.	0.	0.	0.	0.	0.	0.	1.
X_5	0.	0.	0.	0.	0.	0.	0.	0.	1.
X_6	0.	0.	0.	0.	0.	0.	0.	0.	0.
X_7	0.	1.58496	0.	1.58496	0.	0.	0.	0.	2.
X_8	0.	0.	0.	0.	0.	0.	0.	0.	0.
X_9	0.	1.92193	1.	0.918296	1.	0.	0.918296	0.	1.92193

TABLE XVII

THE TRANSMISSION PARAMETER RESULTS

T_{X_i,X_j}	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	6.	5.15564	6.	5.75	5.75	6.	5.5	6.	4.75
X_2	5.15564	2.31128	4.15564	3.90564	3.90564	5.15564	3.73734	5.15564	2.40564
X_3	6.	5.15564	6.	5.75	5.75	6.	4.5	6.	4.75
X_4	5.75	3.90564	5.75	5.5	5.5	5.75	5.25	5.75	3.5
X_5	5.75	4.90564	5.75	5.5	5.5	5.75	5.25	5.75	3.5
X_6	6.	5.15564	6.	5.75	5.75	6.	5.5	6.	4.75
X_7	5.5	3.07068	5.5	3.66504	5.25	5.5	5.	5.5	2.25
X_8	6.	5.15564	6.	5.75	5.75	6.	5.5	6.	4.75
X_9	4.75	1.98371	3.75	3.5817	3.5	4.75	3.3317	4.75	1.57807

The normalized transmission parameter metric is calculated using the (6.2) equation. This calculation provides us with the most significant values representing the pairs of subsystems with the most significant relationship.

$$t(X_i : X'_j) = \frac{T(X_i : X'_j)}{H(X'_j)} \qquad (6.2)$$

TABLE XVIII

THE NORMALIZED TRANSMISSION RESULTS

t_{X_i,X_j}	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	2.	2.3917	2.	2.09091	2.09091	2.	2.2	2.	2.71429
X_2	1.71855	1.0722	1.38521	1.42023	1.42023	1.71855	1.49494	1.71855	1.37465
X_3	2.	2.3917	2.	2.09091	2.09091	2.	1.8	2.	2.71429
X_4	1.91667	1.81182	1.91667	2.	2.	1.91667	2.1	1.91667	2.
X_5	1.91667	2.27572	1.91667	2.	2.	1.91667	2.1	1.91667	2.
X_6	2.	2.3917	2.	2.09091	2.09091	2.	2.2	2.	2.71429
X_7	1.83333	1.42449	1.83333	1.33274	1.90909	1.83333	2.	1.83333	1.28571
X_8	2.	2.3917	2.	2.09091	2.09091	2.	2.2	2.	2.71429
X_9	1.58333	0.920243	1.25	1.30244	1.27273	1.58333	1.33268	1.58333	0.901755

After completing all these calculations, we present our normalized transmission results in Fig. 56. Fig. 56 shows all the relationships between the nine parts with several respective levels of connection and represents the Conant result, which helps us understand the system. As a result of this analysis, we identify that the full nodes in the blockchain can be one of these actors: lab tech, caseworker, treatment provider, or police.

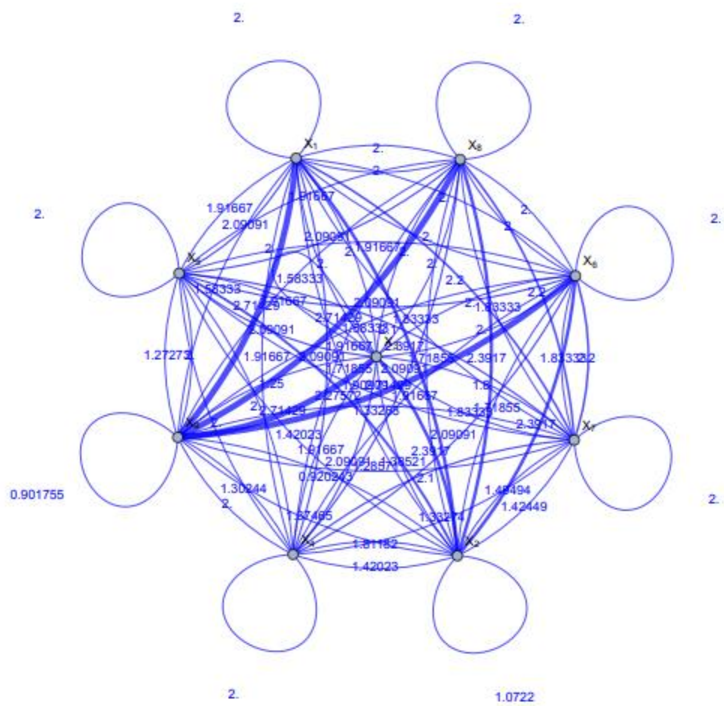

Fig. 56. Conant result demonstrating all the relationships between the nine parts.

6.3.3 Health Monitoring System – LAP

Blockchain has already been applied in the healthcare sector. Healthcare has several challenges and obstacles, and blockchain can solve some of these issues. However, applying blockchain flouts some security and privacy rules in the healthcare system. For example, HIPAA prohibits applying a public blockchain. This step of the framework plays an important role in selecting the full nodes in the blockchain network. Based on our analysis in the previous section, the case manager has several side tasks that affect their main role, which is smoothing out the sequence of services in the health care system. A trusted validated actor is the best entity to work as the full nodes in the blockchain network, which, in our case can be the lab technician, caseworker, treatment provider, or police. We used a MacBook 2.9 GHz Dual-Core Intel Core i5 with 8 GB memory in this experiment.

After analyzing the blockchain system structure concerning the CJP structure mentioned in the previous section, we derived 100 nodes representing CJP blockchain systems, based on Fig. 56. After converting the blockchain system into 100 blockchain nodes shown as a graph, we apply the next steps in the methodology. We apply the LAP in information theory to model and analyze the blockchain systems proposed by [45]. Finding the LAP is accomplished by finding the N-Queens solution, where the N-Queens solution is equivalent to MIS. We developed this process based on previous studies [223, 45, 1, 224]. The process has two steps that convert a blockchain system into a graph and find the MIS, which leads to the LAP. We used Wolfram Mathematica [225, 224] to implement our work. Fig. 57 shows our 100 blockchain nodes, that is, one of the ten attempts. The nodes are connected randomly.

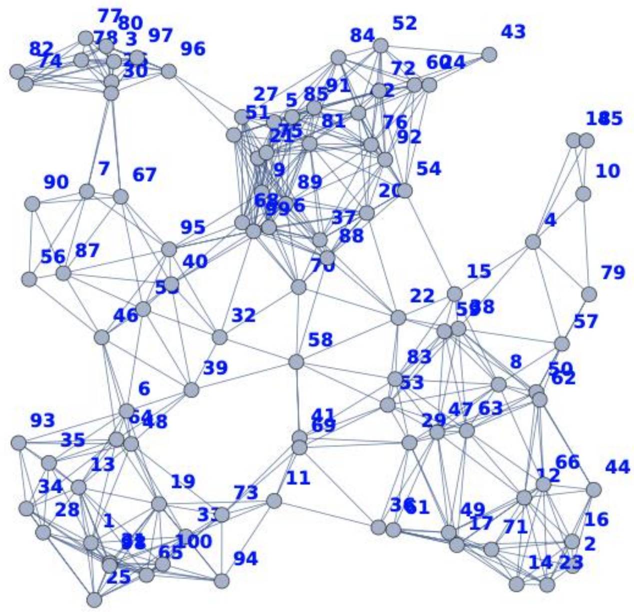

Fig. 57. 100 blockchain nodes.

We ran the experiment ten times. Allehaibi [224] applied this technique in wireless communication systems. He studied the clustering efficiency of this technique; we flowed his steps and added power consumption due to its importance to blockchain. Table XIX illustrates the average clustering efficiency, the percentage of reduced power consumption, and redundancy. We used the Wolfram Mathematica software to calculate the average redundancy and clustering efficiency, which we adapted from [224]. We assumed that the CHs consume one power unit, and the rest of the nodes consume 0.5 power units. We present the clustering efficiency and power consumption calculations below:

$$\text{Efficiency} = \frac{(Number\ of\ Nodes - CHs) * 100}{Number\ of\ Nodes} \quad (6.3)$$

$$\text{Power Consumption} = 100 - \big((Number\ of\ Nodes - CHs) * 0.5\big) + (CHs * 1) \quad (6.4)$$

TABLE XIX

RESULTS OF 100 BLOCKCHAIN NODES AND 10 ATTEMPTS

Attempt	Clustering Efficiency	Reducing Power Consumption	Redundancy
1	79%	39.5%	2.04
2	80%	40%	2.11
3	80%	40%	2.15
4	79%	39.5%	2.24
5	78%	39%	2.24
6	79%	39.5%	2.24
7	79%	39.5%	2.15
8	80%	40%	2.06
9	79%	39.5%	2.08
10	78%	39%	2.28

We found the MIS of this graph and many alternative maximum independent sets that maintain the system's performance. Fig. 58 shows one of the maximum independent sets for the 100 blockchain nodes graph. The red nodes are the full nodes (CHs in any known system), and the blue nodes are the light nodes. This model displays the following advantages: efficiency, reliability, validity, and compatibility. According to Fig. 58, the model has alternative sets that maintain the system's performance, illustrating reliability and validity. In this model, the overall average clustering efficiency is 80%, and the power consumption is reduced by 40%.

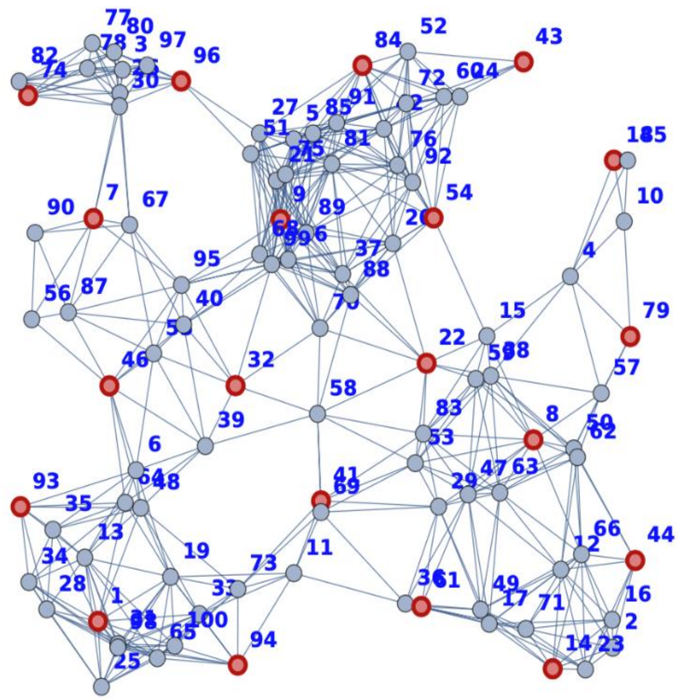

Fig. 58. One of the MIS for the 100 blockchain nodes.

6.4 Results

We proposed a framework with techniques derived from information theory that assists in modeling and designing blockchain systems in a smart city setting. Several researchers have addressed smart cities as a system of systems or a complex system, and modeling complex systems is a challenge. We proposed a modeling approach that generates an innovative blockchain model with capability continuity after modeling. Our framework not only provides an innovative blockchain model with capability continuity , but it also provides a deep understanding of the systems and nearly decomposes them. In addition, the framework minimizes the energy and scalability issues that are currently slowing the adoption of blockchain technology. The framework was applied to a real healthcare system, the CJP, for which we designed a blockchain system.

The framework utilizes the PArchitect tool, Conant analysis, and LAP and uses the three-dimensional approach. The model's principal first step is to determine the smart city context. Thus, by using PArchitect, we obtain a deep understanding of a system. PArchitect is a backward modeling technique that begins from the smart city context, after which a Conant analysis takes place. The Conant analysis plays a significant role in understanding and determining smart city interactions.

There are several smart city models. Some of these models do not consider complexity but rather present smart cities as non-overlapping partitioned linear systems. In reality, the smart city is a complex system. Recently, researchers have proposed smart city models based on complex science. We compare our work with some of them. Table XX illustrates the comparison.

TABLE XX

SMART CITY MODELS COMPARISON

Model	Consider complexity	Capability continuity after modeling	Decomposed	Nearly decomposed	Dynamic
A Framework for Designing Blockchain Systems in a Smart City Setting	✓	✓		✓	✓
The smart cities wheel model (Boyd Cohen, 2013)			✓		
The pattern of collaborative networking (Rădulescu et al., 2020)	✓				✓
Multi-stakeholder (Wai et al. 2018)	✓				✓
CityDNA (Moustaka et al., 2021)	✓				✓

We proposed using information theory to model blockchain systems in a smart city setting. We used the MIS from graph theory as a tool to model LAP. Our proposed model is applicable to all system types [45]. The blockchain architecture's decentralization and distribution network make modeling and analyzing the blockchain network difficult [226]. This model presents the systems and their problems visually. The critical challenge in this method is converting a system to a graph [45]. Gavhale and Saraf [215] compared lowest ID and highest degree. We examined their study to compare our results. Table XXI illustrates the comparison.

TABLE XXI

LOWEST ID, HIGHEST DEGREE, AND LAP COMPARISON

Algorithm	Working	Advantage	Efficiency	Power reduction	Redundancy
Lowest ID	The lowest ID node selected as CH	• Easy to understand • Elected based on unique ID	**83%**	**41.5%**	**1.9**
Highest Degree	The node which is linked by the highest number of node, selected as a CH	• CH elected based on degree • Rate of data transmission is easy and fast	**85%**	**42.5%**	**1.72**
LAP	The node that makes least energy consumption path selected as a CH	• CH elected based on energy • Easy to understand • Alternative sets	**80%**	**40%**	**2.06**

As mentioned in the introduction, concrete, abstract, and mimetic modeling are the main types of mathematical modeling [45]. This model is an abstract model [45]. It compares the behaviors of the natural system and LAP. This model improves the operational efficiency of the blockchain systems in the smart city and makes a significant trade-off between the blockchain's structure and its challenging issues of energy consumption and scalability. By applying this model, these problems will be minimized. Recently, researchers have been proposed solutions to these issues. We compare our work with some of these solutions. Table XXII illustrates the comparison.

TABLE XXII

BLOCKCHAIN SOLUTIONS COMPARISON

Method	Blockchain scalability solution	Blockchain scalability solution's layer	Alternative sets
A Framework for Designing Blockchain Systems in a Smart City Setting	MIS as tool to find LAP	2nd	✓
Red deer algorithm (Nguyen et al., 2020)	RDAC-BC	2nd	
PLASMA (Joseph & Vitalik, 2017)	Child chains	2nd	
Spectre and IOTA (Hafid et al., 2020)	Directed acyclic graph	1st	

CHAPTER 10

CONCLUSION

We have introduced a framework for designing blockchain systems in a smart city setting. Smart cities and their complex architecture and challenges make their analysis and modeling difficult. Therefore, defining the context is critical to modeling smart cities effectively. In addition, smart city models must be able to adapt to any changes. These challenges and the blockchain's scalability and energy consumption issues are considered in our framework.

Our innovative model for a blockchain system in a smart city setting is able to minimize the blockchain's scalability and energy consumption issues and provide alternative sets that maintain the performance of the system. This technique can be used in several fields. In addition, the framework contains useful features that could be used to improve smart city resilience. Creating a blockchain healthcare system that meets all HIPAA privacy and security rules could also be considered for future work.

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