FEDERAL UNIVERSITY OF ITAJUBÁ – UNIFEI
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Communication Technology Selection Method For Smart Energy Metering Based On Analytic Hierarchy Process

Julião Alberto Langa

Itajubá, March 23, 2023

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“Negative results are just what I want. They’re just as valuable to me as positive results. I can never find the thing that does the job best until the ones that don’t.”

(Thomas A. Edison)

Abstract

As new communication technologies continue to emerge and the integration of these technologies into the modernization of the electricity grid becomes increasingly necessary, a variety of communication protocols and combinations are being explored for their potential use in the smart grid domain. However, given the multitude of technological possibilities available, choosing the optimal technology capable of adequately addressing the communication requirements of the intelligent grid remains a challenge for utilities. This is due, on the one hand, to the fact that different intelligent grid applications have different qualitative and quantitative communication requirements. Moreover, on the other hand, each technology has advantages and disadvantages concerning its performance characteristics in such requirements. This work uses the AHP (Analytic Hierarchy Process) methodology to select the wireless technology that presents the best performance characteristics concerning determined requirements. For this, a computational algorithm was developed in the Matlab programming environment, through which criteria such as data rate, latency, range, security, reliability, and interoperability were compared to select the best technological alternative among Wi-Fi, ZigBee, Z-Wave, and Bluetooth. Data collected from the literature review, with the performance characteristics of these technologies, were applied in a single case study simulating the practical implementation of this work. Among the analyzed criteria, simulations demonstrated that Wi-Fi was the winning technology alternative with 32.353%, followed by Z-Wave with 29.865% in second place, and ZigBee and Bluetooth were ranked third and fourth with 25.255% and 12.527%, respectively. In addition, sensitivity analysis shows how the AHP methodology can be a feasible alternative to assist decision-making in the smart grid domain.

Key-words: Smart electric grids. Communication technologies. Communication requirements. Decision-making methods. AHP methodology.

Resumo

À medida que novas tecnologias de comunicação continuam a surgir e a integração destas tecnologias na modernização da rede elétrica se torna cada vez mais necessária, uma variedade de protocolos e combinações de tecnologias de comunicação vem sendo explorados para a sua potencial utilização no domínio da rede inteligente. No entanto, dada a multiplicidade de possibilidades tecnológicas disponíveis, a escolha da melhor tecnologia capaz de responder, adequadamente, aos requisitos de comunicação da rede elétrica inteligente continua sendo um desafio para diferentes atores interessados. Isto se deve, por um lado, ao fato de diferentes aplicações de rede inteligente terem diferentes requisitos de comunicação, quer sejam quantitativos ou qualitativos. Além disso, por outro lado, cada tecnologia tem vantagens e desvantagens relacionadas com as suas características de desempenho em tais requisitos. Este trabalho, portanto, utiliza a metodologia AHP (Analytic Hierarchy Process) para selecionar a tecnologia sem fios que apresenta as melhores características de desempenho relativamente a determinados requisitos. Para tal, foi desenvolvido um algoritmo computacional no ambiente de programação Matlab, através do qual critérios tais como taxa de dados, latência, alcance, segurança, confiabilidade e interoperabilidade foram comparados para selecionar a melhor alternativa tecnológica entre Wi-Fi, ZigBee, Z-Wave e Bluetooth. Os dados coletados na revisão de literatura, com as características de desempenho destas tecnologias, foram aplicados num único estudo de caso simulando a implementação prática deste método em ambiente residencial. Dentre os critérios analisados, as simulações demonstraram que o Wi-Fi foi a alternativa tecnológica vencedora com 32,353%, seguido pelo Z-Wave com 29,865% em segundo lugar, e ZigBee e Bluetooth ficaram em terceiro e quarto lugar com 25,255% e 12,527%, respectivamente. Além disso, a análise de sensibilidade, dos resultados, mostra como a metodologia AHP pode ser uma alternativa viável para auxiliar na tomada de decisões no domínio da rede inteligente.

Palavras-chaves: *Redes elétricas inteligentes. Tecnologias comunicação. Requisitos de comunicação. Métodos de apoio à tomada de decisão. Metodologia AHP.*

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List of abbreviations and acronyms

ADSL	Asymmetric DSL	41
AHP	Analytic Hierarchy Process	6
AI	Artificial Intelligence	91
AMI	Advanced Metering Infrastructure	8
AMR	Automatic Meter Reading	20
ANP	Analytic Network Process	91
BAN	Building Area Network	27
BPL	Broadband PLC	40
CI	Consistency Index	53, 54
CR	Consistency Ratio	54
DC	Data Concentrator	27
DERS	Distributed Energy Resources And Storage	25
DG	Distributed Generation	15
DGM	Distribution Grid Management	25
DR	Demand Response	25
DSL	Digital Subscriber Line	8
DSM	Demand Side Management	20, 26
EMC	Electromagnetic Compatibility	31
EPRI	Electric Power Research Institute	21
ET	Electric Transportation	25
EU	European Union	21
EVs	Electric vehicles	20
FAN	Field Area Network	27
FHSS	Frequency-hopping spread spectrum	31
GGGE	Global Greenhouse Gas Emissions	15
GPRS	General Packet Radio Service	33
HAN	Home Area Network	8
HASL	High Bit-rate DSL	41
IAN	Industrial Area Network	27
IDS	Instruction Detector System	27
IoT	Internet of Things	31
ITU	International Telecommunication Union	39
LoRa	Long Range	8
LPWAN	Low-Power WAN	31
LTE	Long Term Evolution	33

MCDA	Multi-Criteria Decision Analysis	43
MCDM	Multiple Criteria Decision Making	19
NAN	Neighbourhood Area Network	25
NIST	National Institute for Standards and Technology	23
NPL	Narrowband PLC	39
O&M	Operation & Maintenance	42
PLC	Power Line Communication	8
RES	Renewable Energy Sources	15
RI	Random Index	54
RTP	Real-Time Pricing	36
SCADA	Supervisory Control and Data Acquisition	37
SM	Smart Meter	31
USA	United States of America	30
VDSL	Very High bit-rate DSL	41
VSAT	Very Small Aperture Terminal	37
WAN	Wide Area Network	25
WASA	Wide Area Situational Awareness	24
WDM	Wavelength Division Multiplexing	41
Wi-Fi	Wireless Fidelity	6–8
WiMAX	Worldwide Interoperability For Microwave access	8
WMN	Wireless Mesh Network	28

Contents

1 INTRODUCTION

1.1 Research Background

Energy has become an indispensable commodity for any modern economy. This is because it is the essential source for meeting the world's growing demand for electricity. Moreover, it is undeniable that society has developed various techniques for better use of energy resources and conscientious consumption to make these resources cheaper and preserve them for future generations[1].

However, the development of these techniques, or the lack of them, has determined the fate of countries in modern economies so that, those who were able to develop and use them led the industrialization process. On the other hand, those that did not invest in the energy sector and the modernization of the power grid became technologically outdated countries, which harmed their entire social life [2].

To the National Academy of Science [3], the power grid in its current form is one of the most remarkable technological developments of the 20th century. In recent years, the global trend toward environmentally friendly power generation systems has driven the increased use of RES (Renewable Energy Sources) and the increasing complexity and size of power grids [4]. As a result, new concepts for power generation, transmission, and distribution are being developed, including the smart grid concept, which aims to increase operational efficiency and reduce GGGE (Global Greenhouse Gas Emissions) by incorporating intermittent DG (Distributed Generation) systems and utilizing modern communication and computer technologies [5].

In general, SG can be understood as a power grid that uses communication technologies and computer intelligence integrated into AMI (Advanced Metering Infrastructure), at all levels, from the generation to the end user of electricity [6]. Considered the key component of an smart grid [7], AMI is the system that, through bidirectional communication among users and the utility, allows, in real-time, the collection and analysis of data measurement, and enables the intelligent management of several services and applications based on such data, to ensure more excellent reliability, efficiency and offer more quality and security to the grid [8]. Finally, as is to be expected, communication technologies are vital for the modernization of the current electricity grid and its evolution into an smart grid, with all its possibilities [9].

A variety of communication technology protocols and their combinations are employed for different applications in an smart grid. However, given the multitude of technological possibilities available, choosing the optimal technology capable of appropriately addressing the fundamental communication needs of SG remains a challenge for utilities. This is partly due to the fact that, on the one hand, various smart grid applications have varying fundamental communication technology needs regarding throughput, bandwidth, latency, reliability, and data security. On the other hand, every technology has pros and cons [10].

This issue is well-known among distribution network operators, such as those in [11], whose primary metrics for measuring network performance include dependability and security in addition to bandwidth and latency. Satellite communication, which enables the interchange of non-critical data between protection units and provides suitable options for remote control and monitoring, is one of the potential technical alternatives employed in this context. In this case, the guarantee of availability and bandwidth combined with low implementation costs are its main advantages. However, transmission latency and sensitivity to adverse weather events are the main disadvantages of the technology for this specific application. Therefore, it is important to know the performance characteristics of these technologies to select the most suitable technology for a given application on the grid, etc.

In this work, essential communication requirements for smart grid, from qualitative to quantitative perspectives, are thoroughly investigated and the performance of communication technologies employed in AMI is evaluated concerning each one of them. The purpose of this is to compare the main wireless communication technologies applied in intelligent measurement systems and to determine, through the analysis of their performance characteristics, which of these technologies best suits the smart grid requirements in home area network domain applications. It is intended with this, to select the communication technology, whose performance characteristics fully meet the grid requirements, for intelligent metering systems deployed in the household environments.

1.2 Principal Goal

The broad objective of the proposed research aims to identify the optimal communication technology for home-based applications using the AHP methodology in a single case study, considering factors such as security, reliability, interoperability, data rate, latency, and range.

1.2.0.1 Particular Goals

☑ Identify the communication requirements for the optimal performance of a smart grid;

☑ Evaluate and classify communication technologies suitable for smart grid applications;

☑ Compare the performance of wired and wireless communication technologies for intelligent metering applications;

☑ Develop computational algorithms using the AHP method in Matlab programming platform for data simulation and decision making;

☑ Simulate and validate the results through a case study.

1.2.1 Motivation

Any communication technology has specific limitations, which can be combined with restrictions imposed through the grid requirements [12]. Whether wired or wireless, communication technologies operate at various frequencies and have varying power needs, range (maximum distance), and data rates (speeds). Additionally, they have various security mechanisms with various features.

Furthermore, it is crucial to stress that each technology has inherent benefits and drawbacks compared to other technologies for a given application. Additionally, each technology may differ from others in terms of factors such as short or long-range, low or high throughput, low or high latency, high or low reliability, high or low power consumption, high or low equipment costs, strong or weak security and privacy protocols, and many other things. So the challenge is to compare these parameters to know the limitations of each communication technology.

Therefore, given these factors, the importance of knowing the performance characteristics of these technologies is evident, so that different stakeholders, may select, deliberately, the most suitable technology for applications in smart metering systems in home area applications.

From selecting one technology over another, decision-makers often compare several factors that cannot be directly quantified. However, AHP is an ideal tool as it can capture different opinions and convert them into numerical weights, thus allowing for deliberate decision-making. Proposed by professor Saaty in [13], AHP provides a rational decision-making framework when the criteria and alternatives involved are not directly quantifiable. Therefore, AHP is a valid decision-making tool for selecting the ideal technology for data transfer, in an intelligent measurement environment, and this is the reason why it was chosen in this work.

1.2.2 Research Question

According to what was stated above, the research question of this study is posed as:

Which communication technology is more suitable for transferring metering data in applications based on the HAN (Home Area Network)?

1.3 Main Contribuitions

The first contribution of this work is related to the use of the AHP methodology to develop a computational algorithm, capable of comparing complex grid requirements with the performance characteristics of communication technologies, to select the best technologies for data transfer at home domain applications.

The second contribution of this dissertation is an in-depth review of state of the art regarding communication technologies with applications in energy measurement. It analyzes the technologies for the smart grid domain available in the literature review, evaluating their performance characteristics and the advantages and disadvantages associated with each technology.

It is expected that the present work will help professionals working in power utilities and governments to make choices in selecting communication technologies for their grid modernization projects. In addition, this work may be helpful for enthusiasts, developers, and manufacturers of smart home appliances in aligning their technologies with the smart grid protocols and requirements.

1.4 Limitations of the Study

The first limitation is that this work focuses on the Wi-Fi, Z-Wae, ZigBee, and Bluetooth protocols. However, there are many other technologies available that need to be studied. Thus, this work, like many other works, was developed under certain limitations.

The second limitation was due to the high density of judgments required in applications of the AHP methodology, which makes it impossible to consider all the different requirements and communication protocols currently available; the reason why this work only focuses on six requirements and four alternatives.

The last limitation was the lack of time for the study, which made it impossible to include experts and stakeholders with relevant knowledge about the adopted scope to gather inputs and, eventually, ensure that the weights assigned to the evaluation would be accurate.

1.5 Organization of Dissertation

The remainder of this dissertation is organized as follows: Chapter 2 discusses the state of the art concerning the electrical grid. The communication requirements for smart grid performance are also presented. Furthermore, different communication technologies are addressed, with applications in different environments of smart grid. In Chapter 3 an overview and the mathematical concepts of the AHP methodology are presented. In Chapter 4 the methodology used to achieve the proposed objectives is outlined. Chapter 5 presents the results, sensitivity analyses, and respective discussions. Finally, Chapter 6 lists the conclusion of the study and also identifies some important directions for future research.

1.6 Related works

Since the AHP methodology is considered the most widespread in its category and given the extensive amount of literature available in the area, the closest publications chosen as references for this dissertation include one in [14], which handles the energy sector, with emphasis on the use of the same methodology in applications from smart grid, and in [15], which is more comprehensive in solving problems in engineering areas. According to [14], the author's proposed framework provides a new way to select smart meters cost-effectively without compromising sustainability. In [15], the authors used the MCDM (Multiple Criteria Decision Making) tool to assist professionals in deciding which electrical machine to be used in wind generation projects.

One of the most recent works found on the subject, and which also served as the basis for delimiting this work, is in [16], in which the authors used the AHP methodology to evaluate how the quality of smart meters directly affects the stability, safety and economy of the information collection system and the electrical grid.

Another work is presented in [17], proposing a reliability assessment system for a smart electricity meter based on the AHP methodology. For that, the authors used two schemes, one to analyze and evaluate the performance comparison between different functions on the same meter, and the other to compare different meters from different manufacturers.

2 ELECTRIC GRID: COMMUNICATION TECHNOLOGIES

This chapter discusses the state of the art concerning the electrical grid concepts. In addition, the communication requirements of a smart grid are presented. And finally, different communication technologies, with applications in different environments of smart grid are also addressed.

2.1 Overview of conventional electrical grid

Traditionally, conventional electrical grids operate unidirectionally, meaning that energy flows from the generation side to the end-users (consumers) through the transmission and distribution grids. Furthermore, as consumers only act as passive users of this system, they generally do not have access to consumption information and measurement data, that is, most control and monitoring devices for the behaviour of the grid, as a whole, are implemented on utility premises, collecting information and sharing it with energy regulators [18, 19].

Figure 2.1 illustrates the structure of a conventional electrical and typical grid, as well as the predominant direction's flow of energy and information in such kinds of grids. As can be seen in the figure, on the one hand, in this structure, electricity flows in one direction, starting from the generation side, flowing through the transmission grid, reaching the distribution grid and finally being delivered to the loads. On the other hand, the fact that the monitoring and control devices of the system are predominantly under the domain of the operations center causes the data direction, to flow from the entire grid to the utility premises, that is, through the AMR (Automatic Meter Reading) the consumer has little, if any, level of active participation in the energy market [18].

However, the increasing integration of modern technologies such as EVs (Electric vehicles), distribution automation, smart reclosers, energy storage, DG, microgrids, smart meters and RES (Renewable Energy Sources), has driven a growing adoption of a new concept of electric power networks, the smart grid [8]. These technologies allow the injection of energy at both the distribution level and the consumer grids. In addition, emerging DSM (Demand Side Management) strategies and demand-response programs allow consumers to participate in load and power generation balancing [20]. Therefore, to decide issues concerning participation in the energy market, consumers need to have access to more information compared to the conventional electrical grid [21].

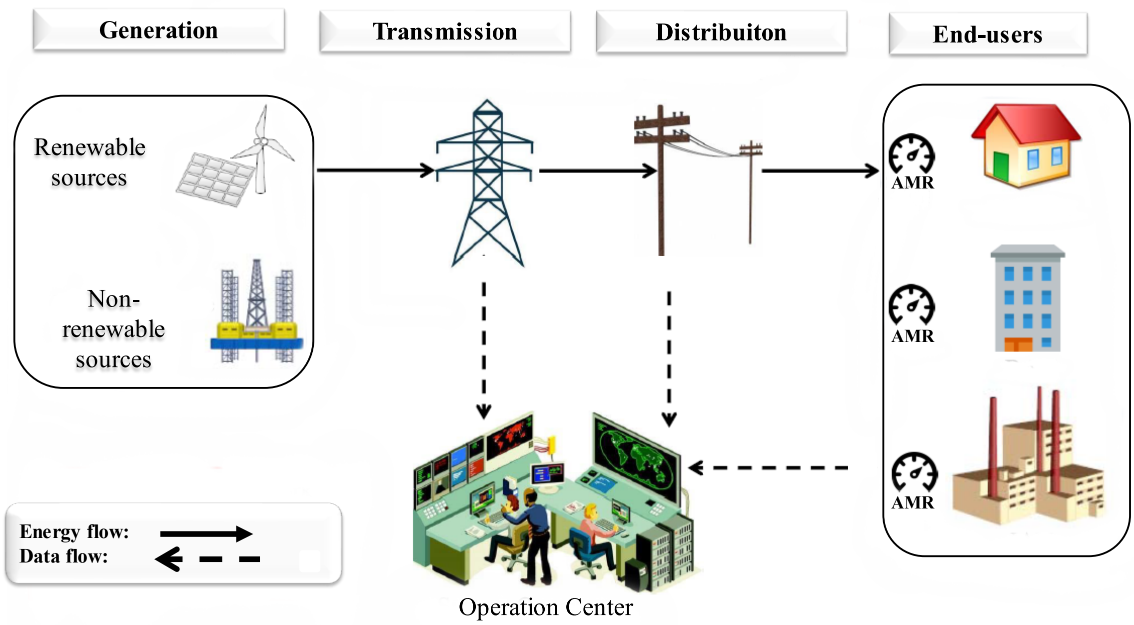

Figure 2.1 – Typical conventional electrical grid [18].

2.2 Overview of smart electrical grid

The concept of an smart grid is addressed in [22], in which the author describes the smart grid as a new concept of the electrical grid that uses advanced communication technologies to monitor and manage in real-time, the entire operation cycle of the electrical system, and whose power and information flow are bidirectional between the energy generation centers and the consumers.

Another smart grid approach was proposed by the EU (European Union) [6], describing smart grid as an electrical grid capable of economically integrating the behaviour and actions of all users connected to it - generators, consumers and those who do both, to guarantee a sustainable and economically efficient energy system, safe, with low-losses and high levels of quality and guaranteed availability.

EPRI (Electric Power Research Institute), by the order side, understands an smart grid as one that incorporates information and communication technology in all aspects of electricity generation, distribution and consumption, to minimize the environmental impact, improve markets, reliability and services, reduce costs and achieve energy efficiency [4].

Although there are different approaches to smart grid, this can, in general, be seen as the use of communication technologies at the service of the electrical grid, aiming to improve efficiency, reliability, security, and guarantee of electricity supply to different users, through the perfect integration of alternative energy generation sources, through automated control and digitization of the grid's life cycle. So, through this bidirectional flow of energy and information, users are no longer passive consumers, but may now, actively, supply their surplus energy to the grid through smart meters that allow monitoring and measuring of exchange [23].

Figure 2.2 represents the paradigm of an smart grid, and the corresponding flow of energy and information. As the diagram in the figure shows, both energy and information follow a bidirectional flow among generating centers and operations center, through transmission systems, and from these through the distribution grid to consumers, and vice-versa.

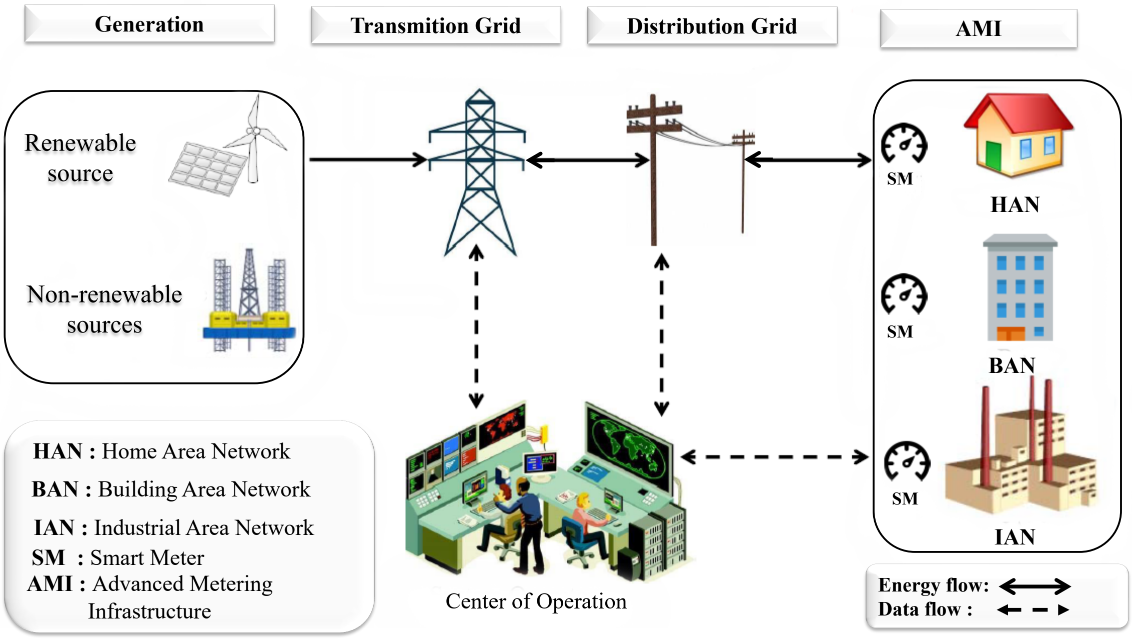

Figure 2.2 – Overview of a typical Smart Grid with its main components [18].

As can be seen in Figure 2.2, an smart grid comprises different components like power plants, transmission and distribution lines and an operations center, from where the entire system is controlled. In addition, it also includes different hierarchical layers, namely, the control layer [24], communication layer [25, 26], security layer [27] and application layer [28]. The communication layer, also known as the AMI, is considered to be the milestone in the modernization of the conventional electrical grid and its evolution to smart grid [23]. AMI is the key component of smart grid which, in addition to bidirectional communication among the stakeholders, also enables regular monitoring load, energy management, smart billing alternatives and integration of new services, etc.

Nevertheless, in [23, 26], AMI is defined as the integration of different technologies that provide an intelligent connection between consumers and system operators, greatly facilitating, in addition to supplying consumers with the necessary information they need to make certain decisions, as well as the ability to execute those decisions, and a variety of choices leading to substantial benefits that normally cannot be enjoyed in a conventional grid environment.

2.3 Communication requirements for smart grid applications

The communications requirements in an intelligent grid consist of two categories, namely, qualitative and quantitative requirements [29]. These requirements vary from application to applications and will influence choices of communication technologies to be selected [30]. Qualitative requirements are subjective requirements that describe the characteristics and attributes of systems, products, or services. These requirements are generally expressed in non-number terms and can include factors such as:

☑ **Security:** which is the ability of the communication infrastructure to combat physical and cyber security attacks to protect the critical data gathered from various smart grid components [31].

According to EPRI, since smart grid entails the transfer of valuable information, the privacy of individuals has given a cause for concern, that is, providing end-to-end security carries the highest priority for almost all smart grid applications. In addition, infrastructure needs to be robust against failures and attacks. Especially for mission-critical applications, such as billing purposes and grid control, security ought to be provided on a communication network to protect the critical assets of the power grid from any vulnerabilities [32].

For instance, in a household context, the communication systems must ensure that devices are well protected from physical attacks, unauthorized entities cannot have access to the metering information, or that sensitive data cannot be modified while in transit in the network. Security is one important reason for deploying private networks. For instance, metering data is gathered from customers, thus it contains much private and sensitive information about customers. The lifestyle of a customer may be revealed if metering data is leaked [33].

☑ **Interoperability:** the ability of diverse systems to work together, use compatible parts, exchange information or equipment from each other, and work cooperatively to perform tasks. Such a requirement is characterized by allowing two or more devices from the same vendor, or different brands, to exchange information and use that information for correct co-operation [34]. In general, according to NIST (National Institute for Standards and Technology), the first international coordinator for smart grid interoperability, there are three main domains of applications for the smart grid network: the high voltage, the network used for electricity transmission, the medium voltage, the network used for power distribution and the low voltage, the network used to provide electricity to end-users. So, as stated in [35], interoperability enables integration, effective cooperation, and two-way communications among the many different and interconnected elements of the smart grid. So, interoperability is an essential requirement for smart grid interoperability, a technical imperative, and the enabler of an open market where innovation can flourish [36].

☑ **Reliability:** a metric of how reliable a communication system can perform data transfers according to the specific requirements. In other words, it refers to the ability of a communication system to transmit data consistently and precisely from one point to another. Thus, a reliable communication system ought to transmit information without errors or delays, even under bad conditions or in high traffic [37].

For [29], reliability is a particularly important consideration in mission-critical or safety-critical applications, where the consequences of a communication failure could be severe. For example, in the context of a smart grid, reliable communication is essential for the accurate and timely transmission of electricity usage data, as well as for the effective control and management of the grid. Similarly, in the context of a HAN, reliable communication is essential for the automation and control of various devices and appliances within households.

☑ **Scalability:** AMI includes millions of smart meters, nodes of smart sensors, smart data collectors, and renewable energy resources. For this reason, scaleability is considered one of the most intuitive requirements for smart grid communications [38]. Defining smart grid scaleability has two perspectives, one is load scalability, which means that communication systems can handle a growing number of devices and data traffic. Another is geographical scaleability, i.e. network size and configuration capabilities [29].

Quantitative requirements are specific numerical standards that systems and devices must meet to function effectively [37]. These requirements are generally expressed in number terms and can include factors such as:

☑ **Date rate:** refers to the maximum amount of data that can be transmitted or processed within a given period. It is a closely related term specifying how fast the data is transmitted between SG components. The data-rate requirements differ for each specific smart grid application. Some of the applications are used to transmit video and audio data, which inquire for high date-rate values to accomplish effective data transfer, such as WASA (Wide Area Situational Awareness) [38]. On the other hand, HAN applications may require the ability to transmit various types of data, such as electricity consumption data, device control signals, and real-time pricing information. So, the communication technology used for such an application should be able to support the required data transmission rates and bandwidth [39, 40].

☑ **Latency:** latency can be described as the delay of the data transmitted between the smart grid components. It also refers to the expression of how much time it takes for a packet of data to travel from one point on the network to another. The requirements for latency differ for different smart grid applications. Some mission-critical applications have tight delay constraints and require the rapid transmission of information, such as distribution automation deployed in substations (within 4 ms) and WASA systems. For other applications, latency is less critical and higher network delays can be tolerated, such as advanced metering infrastructure (AMI) (e.g., most smart meters send their readings periodically every 15 min per day) or home energy management (HEMs) [38, 41].

☑ **Range:** in a smart grid, range requirements refer to the specific criteria that must be met for the system to function effectively within a certain area. It refers to the maximum distance over which a system or device is able to function effectively. This distance may be limited by various factors such as the power of the system's transmitters, the sensitivity of its receivers, or the presence of physical barriers or interference. Other considerations for range in a smart grid may include the ability of the system to accurately measure and report energy usage and demand over a certain area, as well as the ability to maintain a certain level of reliability and security [42]. Nevertheless, range requirements may vary depending on the specific needs and goals of the system, as well as the physical characteristics of the area in which the system is being deployed.

Some specific requirements for communication applications in terms of their data rate, latency, reliability, security and range requirements are summarized in Table 2.1, whose details can be consulted in [31].

Table 2.1 – Communication Requirements for different Applications in smart grid [37]

Application	**Data rate** [*kbps*]	**Latency**	**Reliability** [%]	**Security**	**Range** [*km*]
AMI	10 - 100	2-15s	99.0 - 99.99	High	5 - 10
DR	14 - 100	500ms - min	99 - 99.99	High	5 - 10
DERS	9.6 - 56	20 ms - 15 sec	99.99 - 99.99	High	5 - 10
ET (Electric Transportation)	9.6 - 56	2sec - 5 min	99 - 99.99	Relatively high	5 - 100
WASA	600 - 1500	20 ms - 200 ms	99 - 99.9999	High	5 - 100
DGM	9.6 - 56	300ms - 2s	99 - 99.99	High	10 - 100

2.4 Advanced metering infrastruture - AMI

Engineers combine applications in an smart grid environment based on their bandwidth capacity and speed needs, data rate, and range needed for their successful deployment. This is done in order to optimize their performance, as stated in [43]. An AMI is a hierarchical multilayer architecture, generally classified into different network topologies arranged in different environments such as HAN, NAN (Neighbourhood Area Network), and WAN (Wide Area Network). These topologies have self-compatible data transfer rates and specific ranges. [42].

Table 2.3 presents a hierarchical layered architecture of communication technologies, which support applications in the AMI environment, in terms of data rate and range.

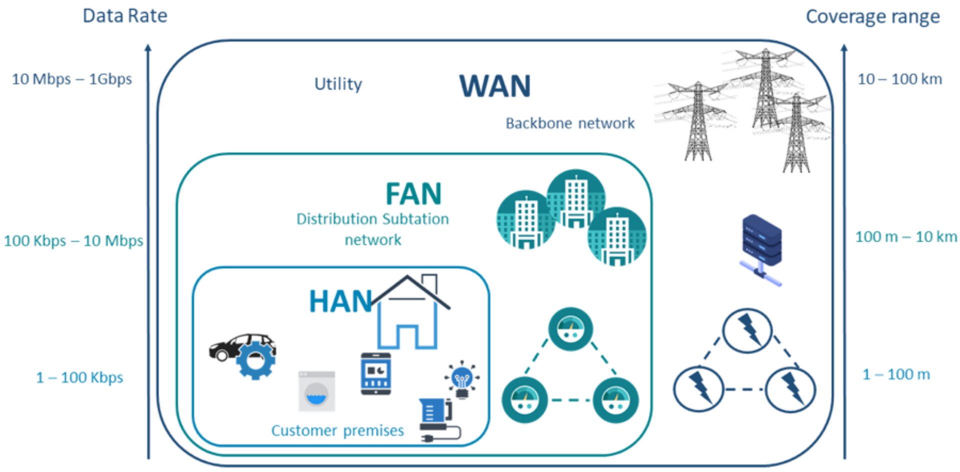

Figure 2.3 – Data rate and range requirements for AMI communication[1]

☑ HAN (Home Area Network):

Having arisen and intensely diffused in the late 1990s and early 2000s, as a consequence of the growth of the internet [6], the HAN network allows communication between household appliances and smart meters, operating over short distances (up to 100 meters) [44]. And, it is implemented in the facilities of the energy consumer, to guarantee the transmission of information between different electronic devices that are inside or near the building. Devices include: smart meters, smart home appliances, smart plugs, chargers for EVs, DSM (Demand Side Management) mechanisms (including demand response), integration of DG, home automation, etc. [8].

HAN also offers the opportunity to monitor and control energy use, which is the basis for the implementation of DSM or demand response programs by the operations center. The smart meter communicates with other home devices to collect data such as energy usage information from energy-consuming devices, the status of RES and the energy produced by these sources, etc., to be sent to the operations center [25].

The internet and technologies initially developed for a HAN network aimed to transfer large amounts of data (high bandwidth) at high speed across a network at somewhat intermittent intervals. This has different applications including graphics, music and video. However, the needs of applications are significantly different in times of smart grid bandwidth requirements [6]. Depending on the physical installation environment, the HAN network can operate via wired or wireless communication (see Tables 2.2 and 2.3). These applications require a low range, high speed or high data transmission rate ($\geq$

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[1] <https://www.ebalanceplus.eu/category/news/smart-grid/>, accessed on July, 20,2022

100$kbps$) and can be managed with low-cost, energy-efficient technologies to provide ease of communication for a large number of users and DC (Data Concentrator) through the NAN network [25, 26].

☑ NAN (Neighbourhood Area Network):

The NAN, or the FAN (Field Area Network), is a bridge connecting HAN and the WAN, that is a network within the distribution domain, which enables the bidirectional flow of information among WAN and local area networks such as HAN, BAN (Building Area Network), and or IAN (Industrial Area Network), which can be done employing wired or wireless communications, both shown in Tables 2.2 and 2.3. The flow of information in this network takes place through the connection of local networks within a neighbourhood through IDS (Instruction Detector System), or a pole-mounted device, also named DC (Data Concentrator) [44]. Smart meters transfer data of the energy consumed by each user and send it to the HAN network. The latter uses the NAN network to send these data to DC for storage [42].

Besides controlling the electricity supply to each consumer, NAN also allows demand response services and distribution automation [42]. The BAN and IAN networks have their applications aimed at the commercial and industrial sectors, respectively. It can therefore communicate normally with building automation systems such as heating and ventilation or energy management systems [43]. Figure 2.4, illustrates a generic AMI architecture and its main components within the smart grid domain.

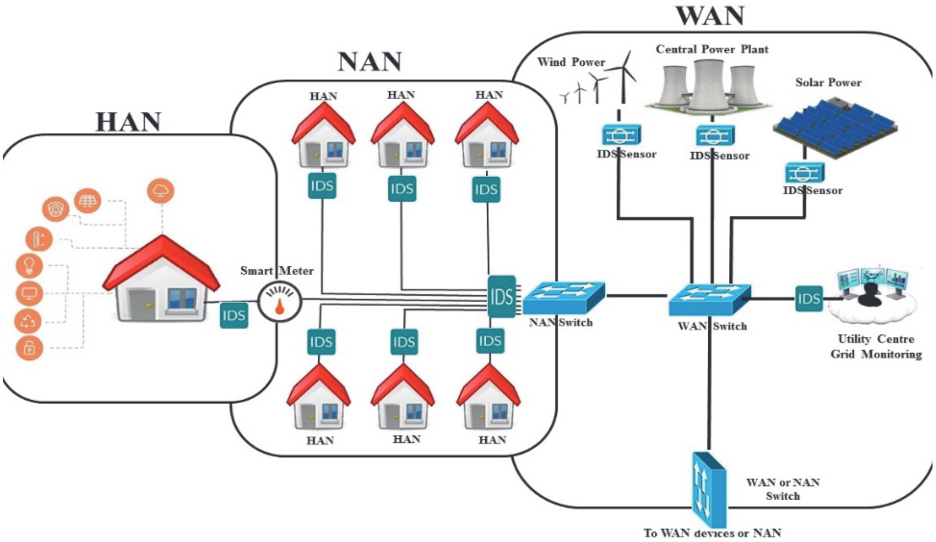

Figure 2.4 – AMI typical architecture and its main components [45].

It's important to note, according to [46], that in the NAN network, data is transmitted from a variety of sources to a DC usually located in substations. This task requires a high data rate (high bandwidth) and a large range. However, due to the changing nature of the physical environment in which NAN/FAN operates, and its range requirements, different technologies for its implementation are used. So, on one hand, when range requirements are lower, the WAN standards of range can be applied; on the other hand, if a high range is required, other technologies will be better suited. Although, both the wired and wireless technologies are applied, in NAN/FAN networks, different communication technologies, such as WMN (Wireless Mesh Network) are used as an alternative.

☑ **WAN (Wide Area Network):**

The WAN network is the communication backbone in the smart grid. This ensures communication between all entities in the system, that is, power plants, transmission and distribution substations, utility premises companies and consumer facilities in general. Also named as core network [42], the applications in the WAN network are expanded over a wide geographic area, thus requiring a larger number of data access points at high rates of up to $1Gbps$ and long-range coverage of up tp $100km$ of distance. For [8], this is the reason why the HAN and NAN networks are incorporated into this network because the real-time measurements performed across the entire electrical grid by measurement and control devices are sent to the operations and control center via WAN. On the reverse, instructions and commands are sent from the operations and control center to the devices, through the same network [44]. High-range coverage and high speed are essential requirements to maintain the stability and reliability of the WAN network. Therefore, the communication technologies suitable for this purpose can be PLC, Optical fibre, Cellular or WiMax. However, for remote locations and/or backup, satellite technology could also be an alternative [2].

2.4.1 Communication technologies for AMI

Two main groups can be distinguished in the smart grid communication technologies, namely, wireless and wired based technologies. On one side the wireless-based technologies are popular choice for smart grid applications, for their flexibility and mobility and can be cost-effective in some cases. On other side, wired-based technologies are another popular choice for smart grid applications due to their reliability, security, and high-speed communication. Nevertheless, there are some drawbacks to using either wired-based or wireless-based technologies in smart grid applications, as outlined in Sections 2.4.1.1 and 2.4.1.2 [47, 48].

2.4.1.1 Wireless-based communication technologies

Here are some of the pros of wireless-based technologies for smart grid applications [47, 48, 9, 28]:

☑ **Flexibility and mobility:** Wireless-based technologies offer greater flexibility and mobility, making them well-suited for applications where wired infrastructure is not feasible or practical.

☑ **Easy deployment:** Wireless-based technologies can be deployed quickly and easily, with the minimal infrastructure required.

☑ **Scalability:** Wireless-based technologies can be scaled up or down as needed, making them suitable for applications of varying sizes.

☑ **Cost-effective:** Wireless-based technologies can be cost-effective, especially for small-scale applications where the cost of wired infrastructure is prohibitive.

Some Cons of wireless-based technologies are also presented:

☑ **Interference:** Wireless-based technologies are susceptible to interference, which can cause communication disruptions and affect the grid's reliability.

☑ **Security:** Wireless-based technologies are generally less secure than wired-based technologies and are more susceptible to hacking.

☑ **Limited bandwidth:** Wireless-based technologies have limited bandwidth compared to wired-based technologies, which can be a challenge in some smart grid applications that require high-speed communication.

☑ **Range:** Wireless-based technologies have limited signal range, which can be challenging in large-scale smart grid applications.

Table 2.2, presents the wireless-based communication technologies comparisons in terms of performance indicators.

Table 2.2 – Comparison of wireless communication technologies for AMI [39, 43, 49, 12]

Technology	**Data rate**	**Latency**	**Range**	**Reliability**	**Power Consumption**	**Interoperability**	**Security**	**Network**		
								HAN	**NAN**	**WAN**
ZigBee	up to 250 *kbps*	15 ms	up to 100 m	High	Low		✓	✓		
Z-Wave	up to 100 *kbps*	100 ms	up to 100m	High	Low	✓	✓	✓		
LoRa	up to 50 *kbps*	2 *s*	up to 8 *km* (in urban) up to 22 *km* (in rural) up to 45 *km* (in flat)	Low	Low	✓	✓		✓	
Cellular	2G: 100 *kbps* 3G: 2 *Mbps* 4G: 450 *Mbps* 5G: 10 *Gbps*	up to 1000 *ms* 200 *ms* 10 *ms* 1 *ms*	50 *km* up to 50 *km* up to 50 *km* up to 300 *m*	Medium	High		✓		✓	✓
Wi-Fi	up to 150 *Mbps*	150 *ms*	up to 300 *m*	Medium	High	✓	✓	✓		
Bluetooth	1 *Mbps*	34 *s*	10 *m*	Low	High	✓	✓	✓		
WiMAx	up to 75 *Mbps*	up to 50 *ms*	up to 50 *km*	High	Low	✓	✓			✓
Satellite	up to 1 *Mbps*	250 *ms*	up to 6000 *km*	High	Low	✓	✓			✓

☑ **ZigBee:** It is one of the main broadband wireless technologies based on the IEEE 802.15.4 protocols, characterized by low data rate, low complexity, low deployment cost, and ultra-low power consumption [50]. This technology was developed by the ZigBee Alliance in 2002 and is quite popular in applications that require lower data rates, more battery backup and short-range applications. Due to these characteristics, it is widely used in home automation devices, health care, building automation, wireless lighting on/off switches, interactive toys and electrical meters with home displays [40].

ZigBee operates in three different frequency bands, $2.4GHz$ with 16 channels (worldwide used), $915MHz$ with 10 channels (used in USA (United States of America)) and $868MHz$ with one channel (used in EU) [51], with the most commercially available equipment for data transmission over the ZigBee protocol. Depending on environmental conditions and power output, the ZigBee range is, also, strongly influenced by antenna size, ranging up to $100m$ within the sight line and can connect with up to 65000 devices on the same mesh [52, 53].

Overall, Zigbee is a good option for several low-power and low-data-rate applications, including industrial control, building automation, and home automation, as well as applications that: need less power; have a reasonable amount of bandwidth; are inexpensive; and have a lot of users. However, its shortcomings in terms of data rate, short range, restricted compatibility with products from various manufacturers, and complexity can make it less suited for other kinds of applications [38, 54].

Figure 2.5, illustrates a generic ZigBee topology and its network characteristics within HAN.

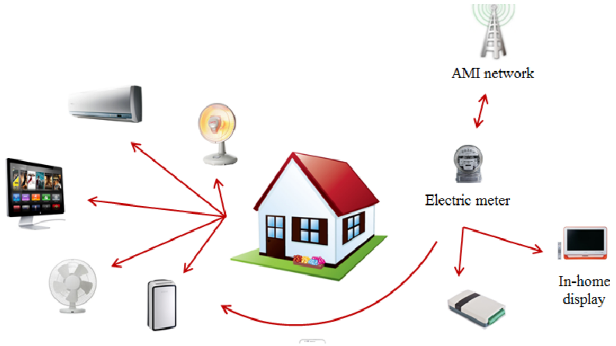

Figure 2.5 – ZigBee topology [55]

☑ **Z-Wave:** In [56], it is stated that Z-Wave is a new low-power consumption wireless home automation technology with FSK and GFSK modulation. It communicates at a frequency of $868MHz$ and $900MHz$ and a range of about 30 meters (indoors) to $100m$ (outdoors), with a data transmission rate between 9 and $40kbps$. It makes devices double the signal like repeaters and due to its frequency operation, it does not have to handle the often crowded $2.4GHz$ band, that ZigBee and Wi-Fi use. For instance, it has network reliability that enables it for further applications.

Z-Wave is mainly used for control and monitoring applications and does not allow any interference with Wi-Fi or any other 2.4GHz wireless technology, furthermore with the short-range features and low data rate, the Z-Wave is a good candidate for smart grid applications on HAN home networks, being able to support smaller mesh networks of up to 232 devices [54]. In UK[2], SM (Smart Meter) implementation programme was introduced by Energy Demand Research Project in 2007. Ireland's major utility SM rollout in 2014. Both coutries use ZigBee protocols for metering purposes in HAN applications [57].

Overall, Z-Wave is a useful wireless networking protocol for certain types of applications, particularly those that require low power consumption, robustness, and compatibility with a wide range of devices. However, its limited range and bandwidth may make it less suitable for other applications [38, 58].

Figure 2.6, illustrates a generic Z-Wave topology and its network characteristics within HAN.

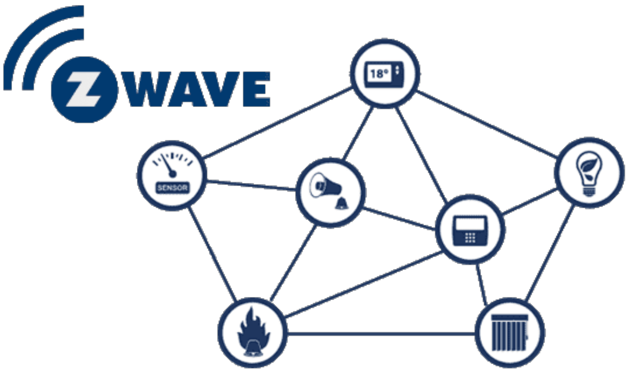

Figure 2.6 – Z-Wave topology [3]

☑ **LoRa (Long Range):** is a wireless modulation for long-range and low-power applications developed by Semtech in the 1940s [59]. Defined by the LPWAN (Low-Power WAN) protocols, the LoRa technology emerged in the context of IoT (Internet of Things). According to [60, 61], LoRa was initially used for military purposes because the range of LoRa is $5km$ for an urban area and $20km$ for a rural area, as well as its latency of $2sec.$ in average.

LoRa works below $1GHz$ and has the characteristics of ultra-long-distance and low power consumption data transmission technology. LoRa uses FHSS (Frequency-hopping spread spectrum) technology, which not only maintains the low power consumption characteristics, but also increases its communication distance, and also improves the anti-interference capability, that is, EMC (Electromagnetic Compatibility) [62]. According to [63] and [61], due to the high costs of new generation equipment and its low data rate $(0.3 - 50kbps)$, LoRa technology is currently less used in the field of intelligent distribution networks.

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[2] <http://news.bbc.co.uk/2/hi/business/8023507.stm> accessed on Jun 10, 2022

[3] <https://ihomefuture.com/z-wave-wireless-technology/> accessed on October 21, 2022

Benefits: long-range; less power consumption; low cost; wide range; easy to deploy. Challenges: network size is limited; not ideal for devices operating with a high data rate.

Figure 2.7, illustrates a generic LoRa topology and its network characteristics within the NAN environment.

Figure 2.7 – LoRa topology [4]

☑ **Bluetooth:** Bluetooth is a fast-growing communication technology based on the IEEE 802.15.1 standard protocol, characterized by being of low power consumption and a nominal range of the order of at least 10 m, reaching up to 1 Mbps in data transmission capacity, supporting bandwidth frequencies ranging between 2.4 GHz and 2.48 GHz [64].

For [40], most standalone smart devices are based on Bluetooth technology. Many of these devices do not require a centralized system but can communicate directly with a smartphone or tablet. Bluetooth, therefore, was designed for inexpensive, short-range devices to replace computer peripheral cables, such as computer mouse, keyboards, joysticks, and/or printers. The nominal range of Bluetooth is 10 meters. In most cases, this is not enough to be used in centralized home automation systems, which is why most Bluetooth-based devices are standalone. Nevertheless, Bluetooth offers weak security compared to other technologies [65].

For instance, Bluetooth is proposed for a user-vehicle-charging system, in which an electric vehicle has a wired plugin connection with a charging station and wireless connection via Bluetooth between the charging station and the driver's mobile so that the driver can get information on the charging status, as is shown in [66]. In [67], Bluetooth application has been used for monitoring and management of a power system. As mentioned above, Bluetooth has been used in short-range communications in smart grid applications. It can also be applied for short-distance communications such as generation and consumption data transfer to smart metering management systems [68].

Bluetooth operates using star topology. This means that there is a central device called the hub, which is the central connection point to other devices. These other devices

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[4] <https://enless-wireless.com/en/lora-range/> accessed on October 21, 2022

are called nodes, connected to the hub and able to communicate with each other through the hub. In the Bluetooth network, hubs are usually Bluetooth-compatible devices, such as mobile phones and computers, and nodes are other Bluetooth-compatible devices, as it can be seen in Figure 2.8.

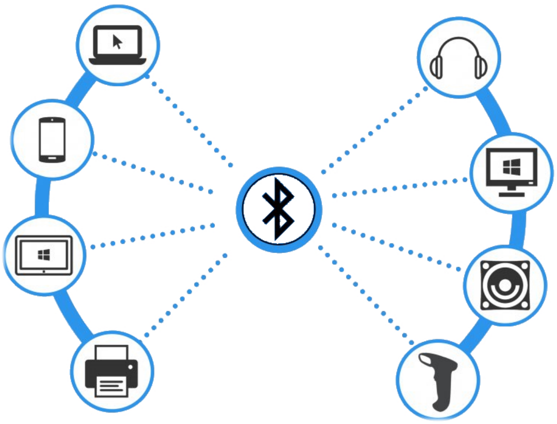

Figure 2.8 – Bluetooth topology [5]

Bluetooth benefits include, low power consumption; low bandwidth requirement; not much expensive; and simple to use. However, its challenges include, limited range; not suitable for large data transfer; ideal for short-range communication only.

☑ **Cellular:** is a radio network that uses a large nuumber of transmitters to create cells, and can be used to enable communication among different components and devices in an smart grid environment. Cellular systems allow reusing frequencies to increase both range and capacity. The telecommunications industry divides cellular technologies into five generations that are labeled , such as 2G (GSM), GPRS (General Packet Radio Service), 3G (UMTS), 4G LTE (Long Term Evolution), and 5G [69]. Cellular systems commonly operate in 850, 900, 1800, and 1900 MHz frequency bands. This technology is considered efficient, however, it has variable performance and latency times that depend on the number of devices that share the service simultaneously. Furthermore, its operational structure is useful to provide services that do not require a constant transmission rate, therefore, it can be successfully applied in the smart grid communication infrastructure.

According to [70], different technologies such as 2G, 3G, and even 4G that are deployed in smart grid networks, have their applications aimed at raising awareness about energy consumption, support for a large number of simultaneous cellular connections, high service coverage and prioritized data routing. Also, this system is used for online billing when the balance is too low, and for home automation to turn electrical appliances on/off. Overloaded electrical appliances can be turned on/off automatically by this technology [71].

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[5] <https://www.cgeniae.tk/> accessed on October 21, 2022

Cellular technology typically uses a star topology where each cell tower functions as a hub and the mobile devices in that cell are the nodes, this communicates with the cell tower, which relays their communications to other cell towers or the broader network. However, there are some variations of cellular technology that use a mesh topology, where each device is connected to multiple other devices and all the devices work together to route communications throughout the network. This can provide more robust and flexible communication, but it also requires more complex technology and infrastructure. Italy, France and USA, all have deployed Cellular based AMI topologies on their WAN domains [72, 57].

Some advantages of using Cellular networks in smart grid applications include: stable networking; large vendors and service provider; infrastructure available. However, there are also some disadvantages of using Cellular technology, including: licensed spectrum; latency issues; security/privacy issues [38].

Figure 2.9 illustrates a generic Cellular topology and its network characteristics within smart grid.

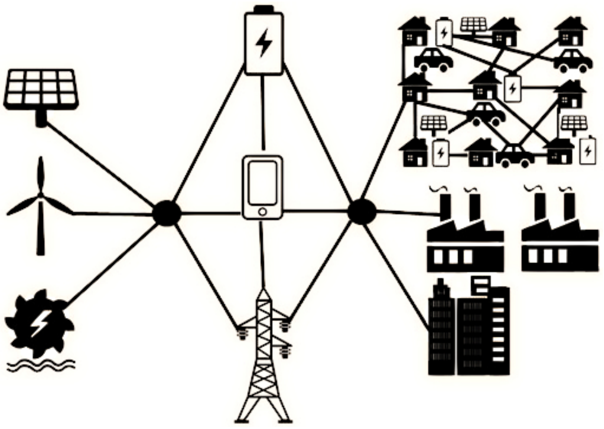

Figure 2.9 – Cellular network topology [73]

☑ **Wi-Fi:** it is a very popular and developed wireless local area network (WLAN) technology and adopted in-home applications all over the world. It operates in an unlicensed band and is subject to interference because several other technologies also share the same spectrum. Technological innovations are leading the Wi-Fi network to low-cost communication. It is a much preferable technology for HAN architecture. However, the citywide Wi-Fi infrastructure also supports NAN and WAN applications. The typical data rate of the Wi-Fi network is up to $150 Mbps$ over a distance of up to $100 meters$ [74].

Based on IEEE 802.11 and widely used in cell phones, smart homes, automation and networks, Wi-Fi performs similarly to the Ethernet network, but no cabling or wiring is required. Typically operates in the $2.4 GHz$ or $5 GHz$ frequency band, which is not licensed worldwide. Compared to Zigbee, the main advantages of Wi-Fi are its fast speed and high flexibility. The maximum data rate can reach $150Mbs$, which means that Wi-Fi has the potential to be applied in large-scale networks for sharing resources, aggregating data and even transmitting big data [48].

Wi-Fi networks can use either a star topology or a mesh topology. It depends on the specific requirements and constraints of the smart meter application. Both star and mesh topologies have their advantages and disadvantages, and the best choice for each application will depend on factors such as the number and distribution of meters, the need for communication redundancy, the availability of power and infrastructure, and the cost of the project. In general, a star topology may be more suitable for a small-scale smart meter deployment with a limited number of meters and a central hub for data collection, Figure 2.10.

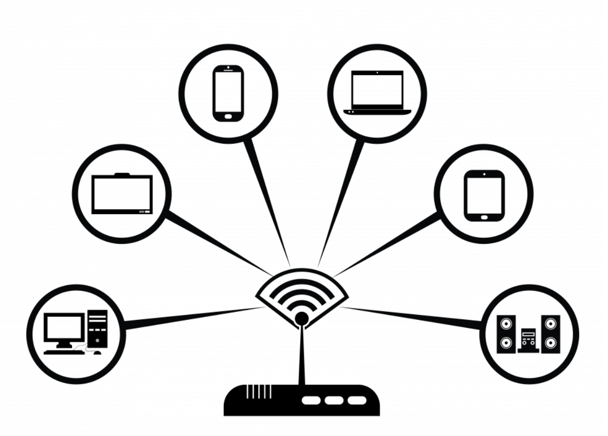

Figure 2.10 – Wi-Fi star topology [6]

A mesh topology may be more suitable for a larger-scale smart meter deployment with a large number of meters distributed over a wide area. In a mesh network, each meter can act as a relay for other meters, allowing communications to be routed through multiple paths. This can provide more robust and reliable communication, especially in cases where there are obstacles or interference that could disrupt a single point-to-point link. However, it may also be more complex and expensive to set up and maintain a mesh network. In Ireland the major utility also deployed Wi-Fi in HAN applications [72, 57].

Wi-Fi and Bluetooth operate on the 2.4 GHz bandwidth which manages a lot of traffic among devices that consume a lot of power. Also, Wi-Fi uses star topology - therefore, it suffers from single-point failure. When an access point is not available, all other devices connected to that access point will be disconnected. The installation cost for Wi-Fi is also, relatively, high [9]. Low cost; widely used; table network are some advantages of using Wi-Fi. However, its challenges include, not being available in all areas; short range; security and privacy issues, more power consumption [38].

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[6] <https://www.digitalunite.com/using-internet/connecting-internet/how-connect-wifi> accessed on October 21, 2022

☑ **WiMAX:** It is a wireless technology, based on the IEEE 802.16 series of protocols. It provides a maximum data rate of up to 75 Mbps at a range of 50 km and low latency of 10 – 50ms. The WiMAX standard natively supports real-time, high data rate, two-way broadband communications such as remote monitoring, RTP (Real-Time Pricing), etc. However, deploying WiMAX can be very expensive as WiMAX towers are based on relatively expensive radio equipment, meaning that WiMAX is not widely adopted as a wireless platform for smart network applications. Besides it, WiMAX frequency greater than 10GHz results in short wavelengths, making it difficult to pass through obstacles. What's worse, WiMAX performance can be affected even by bad weather conditions. Therefore, at present, WiMAX may not be a suitable candidate for intelligent network communications [29].

According to [75], WiMAX can transmit application data from terminal devices enabled with wireless communication technologies like ZigBee or Wi-Fi over NAN and WAN. The data generated by smart meters is transferred from the data concentrators to the base stations WiMAX connected in the backend. WiMAX is a good choice for more data to be transmitted at a lower cost, promising to deploy advanced real-time application control with wider bandwidths. It also supports advanced smart grid applications oriented towards distributed automation, control, monitoring, management and fault finding. The typical WiMAX data rate is up to 1$Gbps$ over range of up to 100km. Nevertheless, its power consumption is a function of its range [76]. The USA Southern California Edison deployed WiMAX topology in their smart grid rollout programme for WAN domain [72, 57].

Figure 2.11, illustrates a generic WiMAX topology and its network characteristics within WAN.

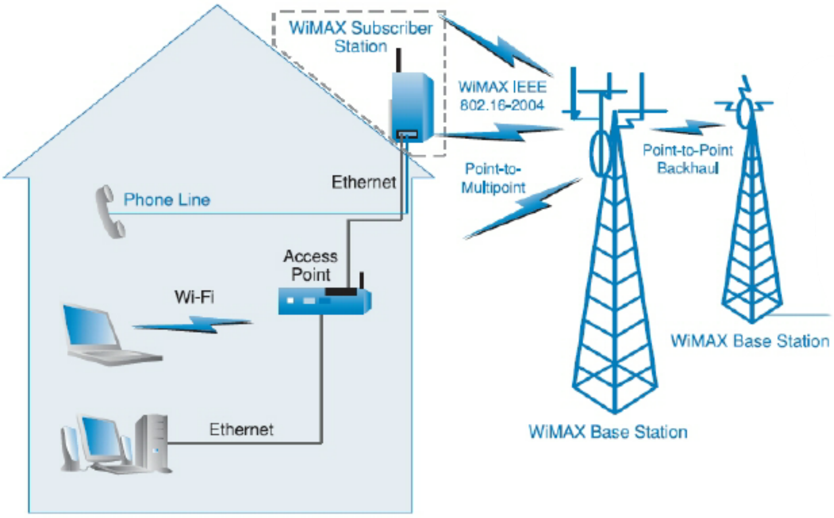

Figure 2.11 – WiMAX topology [77]

WiMAX is a wireless broadband technology that uses a mesh topology, where each base station is connected to multiple other base stations and all the base stations work together to route communications throughout the network. This allows to cover large areas and provide robust and flexible communication for a variety of applications, including smart meter deployment, Figure 2.11.

Some benefits of using WiMAX include, efficient; fast speed; large variety of gateways. However its challenges include: complex network; high cost; licensed spectrum [38].

☑ **Satellite:** Satellites are usually used for communication purposes in vehicles, planes TV, and radio broadcasting [78]. The power and frequency bandwidth of satellites depend on several factors i.e. the size of footprint, complexity, and ground stations. Furthermore, it is also used for weather forecasting, military applications, and navigation purposes [79]. Geographical deployment of smart grid utilities raises the issue of accessibility. With recent advances in satellite technology, broadband and WAN networks can be replaced by virtual satellites. Using smart grid for backhaul networks and another smart grid infrastructure eliminates the need for the Internet. The satellite has been used to provide SCADA (Supervisory Control and Data Acquisition) connectivity and distant communication among remote substations. The VSAT (Very Small Aperture Terminal) can support bidirectional data rates of up to $1Mbps$ along with a range of $6000km$. By using dual frequency and dual access, network availability can be achieved up to 99.9% [11].

Its benefits may include, eliminating the need for a backhaul network in the smart grid; range area of up to $6000km$; data rate of up to $1Mbps$; through satellite, the quality of the transmitted and received signal is better than optical fibre; most economical solution for remote area communication; without any additional cost, several extra users can be accumulated in the given satellite communication; highly reliable and flexible because of global availability; data loss is marginal in satellite communication. However satellite challenges may be related to its high investment and maintenance cost.

Satellite communication systems can use either a mesh topology or a star topology, depending on the specific design of the system. In a mesh topology satellite system, each satellite is connected to multiple other satellites and all the satellites work together to route communications throughout the network. This can provide more robust and flexible communication, especially in cases where there are obstacles or interference that could disrupt a single point-to-point link. However, it may also be more complex and expensive to set up and maintain a mesh network. In a star topology satellite system, there is a central hub satellite that serves as the connection point for all the other satellites in the network. The other satellites, called “remote” or “user” satellites, communicate with the hub satellite and can also communicate with each other through the hub. This can be simpler and more cost-effective to set up and maintain, but it may be less resilient to disruptions (see Figure 2.12).

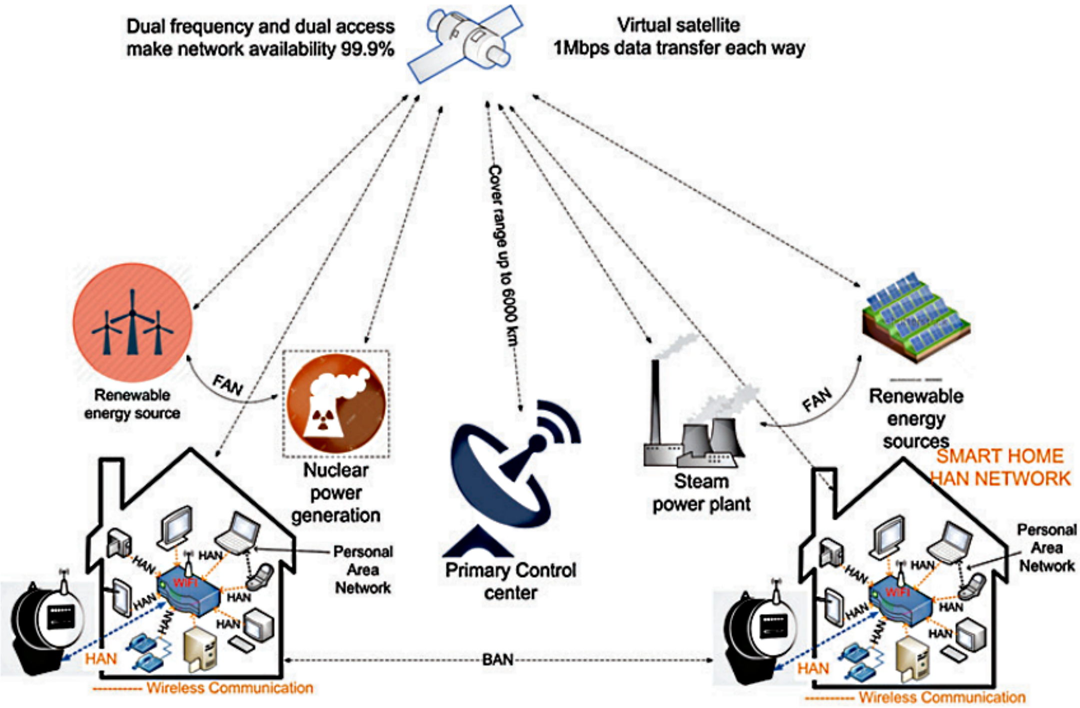

Figure 2.12 – Satellite network topology [12]

2.4.1.2 Wired-based communication technologies

Here are some pros of wired-base technologies [47, 48, 9, 28, 11]:

☑ **Reliable:** Wired-based technologies are known for their reliability, essential for critical applications like smart grid systems.

☑ **Data-rate:** Wired-based technologies offer high data-rate communication, which is necessary for real-time grid control and monitoring.

☑ **Secure:** Wired-based technologies are generally more secure than wireless-based technologies as they are less susceptible to interference and hacking.

☑ **Cost-effective:** Wired-based technologies can be cost-effective compared to wireless-based technologies as they require less infrastructure.

Some cons of wired-base technologies are also apresented:

☑ **Limited mobility:** Wired-based technologies are limited in mobility and flexibility, which can be challenging in some smart grid applications.

☑ **Maintenance:** Wired-based technologies require regular maintenance and can be challenging to repair or replace if damaged.

☑ **Limited Range:** Wired-based technologies have limited range, which can be challenging in large-scale smart grid applications.

☑ **Deployment time:** The deployment time for wired-based technologies can be longer than wireless-based technologies, as they require more infrastructure.

Table 2.3, presents the wired-based communication technologies comparisons in terms of performance indicators.

Table 2.3 – Comparison of wired communication technologies for AMI [39, 43, 49, 12]

Technology	**Data rate**	**Latency**	**Range**	**Reliability**	**Power Consumption**	**Interoperability**	**Security**	**Network**		
								HAN	**NAN**	**WAN**
Optic-Fiber	PON: up to 155 *Gbps* WDM: up to 40 *Gbps* SONET: up to 10 *Gbps*	3.34 μs	60 *km* 100 *km* 100*km*	High	Low	✓	✓			✓
DSL	ADSL: 1 - 8 *Mbps* HDSL: 24 *Mbps* VDSL: 15 - 100 *Mbps*	10 - 70 *ms*	up to 5 *km* ut to 3.6 *km* up to 1.2 *km*	Medium	Low	✓	✓		✓	✓
PLC	HomePlug: 4.5 - 10 *Mbps* NB-PLC: 10 - 500 *kbps* BB-PLC: 300 *Mbps*	10 - 70 *ms*	up to 200 *m* ut to 3 *km* up to 1.5 *km*	Low	High			✓	✓	

☑ **PLC (Power Line Communication):** data communication over the electrical grid, as the name suggests, uses existing power cables as a means of data transmission. PLC is known as a promising communication technology for applications in smart grid due to the availability of the energy infrastructure and therefore has a low installation cost [80].

PLC can be used in almost the entire structure of the smart grid, from low-voltage domestic applications to high-voltage grid automation [81]. This is particularly true for applications in rural areas with access to the energy available but lacking in communication infrastructure and beyond. Because the technology has been in use for decades, in commercial broadband, and because it is highly reliable, PLC provides high throughput and relatively low latency, making it suitable for various applications including in densely populated areas. Generally, PLC is classified into two categories namely:

☑ **NPL (Narrowband PLC):** Widely preferred in smart metering and home automation applications, *Low data Rate NPL* can be easily found in some applications such as IEC 61334-5 based metering systems, x10 and *HomePlug C&C*, which allow local and remote monitoring and management of devices connected to a single network. The second category, in turn, *High data Rate NPL*, can consist of hundreds of kbps of data using multiple carrier modulation schemes, such as orthogonal frequency division multiplication. According to *Powerline Related Intelligent Metering Evolution (PRIME) Alliance*, G3-PLC *High data Rate NPL* has industrial and long-range applications, recommended by ITU

(International Telecommunication Union).

☑ **BPL (Broadband PLC):** broadband technology has an operating range of 2–250 MHz with data rates of up to several hundred Mbps. Standards developed for this include IEEE 1901, TIA-1113 (HomePlug 1.0), ITU-T G.hn (G.9960 / G.9961), HD-PLC, etc. Broadband PLC (BPL) is a method of PLC that allows relatively high-speed digital transmission over public electrical power distribution wiring. In addition, it uses higher frequencies and a wider bandwidth range, which results in a higher data rate for shorter-range applications [82].

PLC has been deployed in many countries worldwide, like Italy, France, Brazil as pilot project, and in the USA all for the HAN applications [72, 57].

Figure 2.13, illustrates a generic PLC topology and its network characteristics within smart grid.

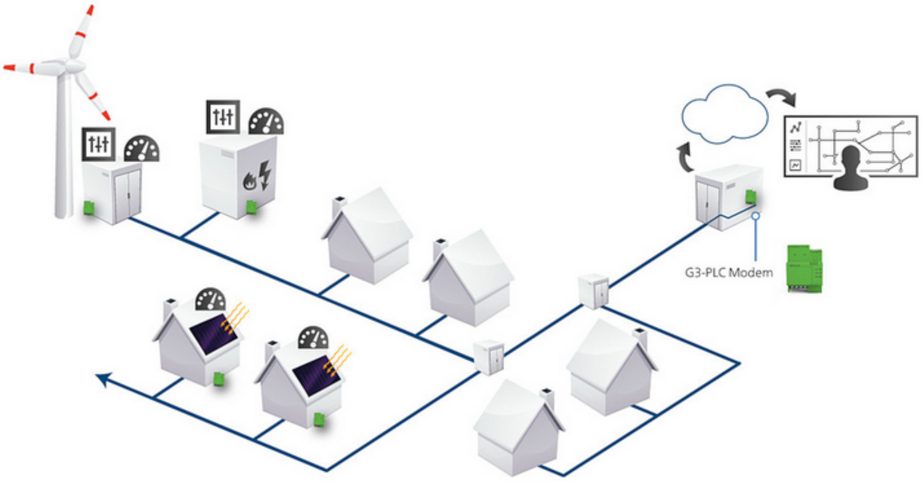

Figure 2.13 – PLC topology [7]

Among the benefits there are: low cost; wired technology. Due to its vulnerability to electromagnetic and radiofrequency disturbances, low bandwidth, and difficulties transmitting large volumes of data over power distribution systems, PLC does have certain drawbacks. According to as stated in [83], security issues are another drawback of PLC Channel distortion; complex routing, a high level of interference that makes it unreliable in residential settings; strong consumer applications, but no facilities for achieving utility goals.

☑ **Fiber-Optic:** optic communication infrastructure, with its extremely low latency data traffic (below 5 microseconds per kilometer) and extremely high speeds, has been

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[7] <https://homegridforum.org/wp-content/uploads/2019/05/devolo-ITU-T-G.hn-solution-for-German-Smart-Grid-Rollout_HGF-at-IEEE-ISPLC-April-2019_George-Hallak.pdf> accessed on October 21, 2022

employed as a substitute for services. With a single wavelength, its data transfer rate can reach 10 Gbps, and with WDM (Wavelength Division Multiplexing), it can reach 40*Gbps* to 1600*Gbps*. Optical/electrical transducers used in Fiber Optic communication are an ideal choice for smart grid due to their excellent capabilities for detecting and measuring current and voltage values of electrical energy [79].

Fibre-optic is already widely used by telecommunications companies to transmit telephone and internet signals. Currently, the high installation costs associated with its deployment complexity make it a more suitable solution for situations where high data transmission rates are required [84]. For example, in the WAN network to communicate energy market information and real-time data between different network users, when distances exceed the limits of cheaper technologies.

Overall, fiber-optic technology is a suitable choice for applications that require fast, reliable, and high-bandwidth data transmission. However, its limited availability and high cost may make it less suitable for other types of applications.

Figure 2.14 illustrates a generic fiber-optic topology and its network characteristics within smart grid.

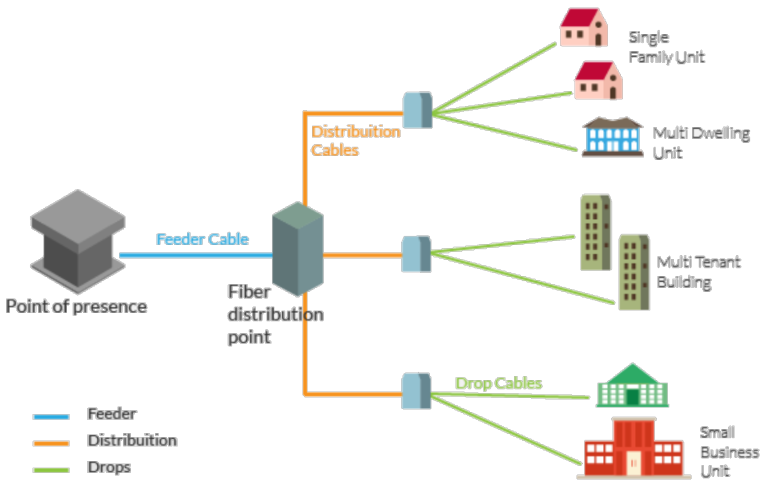

Figure 2.14 – Fiber Optic topology [8]

☑ **DSL (Digital Subscriber Line):** is a set of technologies that use wires from the telephone network for the digital transmission of data, avoiding the additional cost of implementing their new communication infrastructure by utility premises [29]. Depending on the line length, DSL has different types and variable data rates, namely, asymmetric digital subscriber line ADSL (Asymmetric DSL) with a data transfer rate of up to 8 Mbps, HASL (High Bit-rate DSL) which allows about 54 Mbps in data transfer rate and VDSL

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[8] <https://www.targetso.com/tag/fibra-optica/> accessed on October 21, 2022

(Very High bit-rate DSL) whose data transmission capacity exceeds about 52 Mbps [39, 85]. However, according to [39], its efficiency decreases as distance increases; as a result, DSL can only operate over relatively short distances, which justifies its predominance in urban areas, mainly, while in rural areas, this technology remains less developed. Furthermore, the costs of O&M (Operation & Maintenance) are relatively higher.

Despite its high O&M costs, the consolidated diffusion of its infrastructure in the market, as well as its well-tested reliability, constitute the main advantages of using DSL technology in smart grid applications. Therefore, the standard protocols, data transmission rates, range, as well as the types of networks applicable to this type of technology are presented in Table 2.3.

Figure 2.15 illustrates a generic DSL topology and its network characteristics within smart grid.

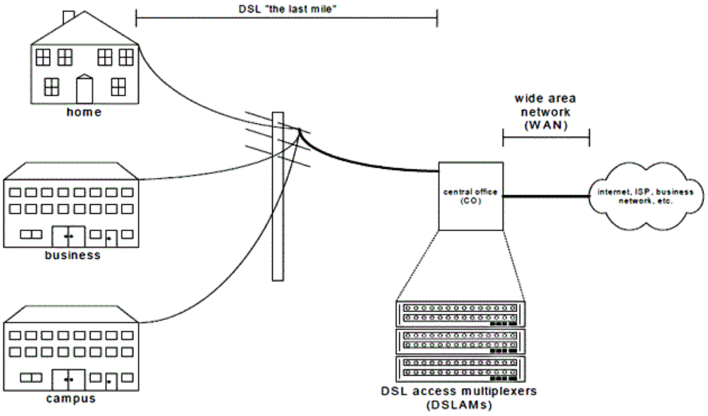

Figure 2.15 – DSL topology [9]

Overall, DSL is a useful broadband technology for certain applications, especially in areas where other options are not available or are not economically feasible, as well due to low cost; widely used; stable network. However, the limitations in speed and distance may make it less suitable for some applications that require higher speeds or are far away from telephone exchanges, not available in all areas; short range and security, and privacy issues.

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[9] <http://eti2506.elimu.net/DSL/DSL_Default.html> accessed on July 11, 2022

3 Analytic Hierarchy Process

AHP (Analytic Hierarchy Process) is one of the leading mathematical models currently available to support decision theory. This chapter addresses the overview and mathematical concepts of the AHP methodology.

3.1 Decision-Making Theory

A decision-making process consists of selecting and implementing the most appropriate solution to achieve the best level of performance. It is expected that this decision-making may be conducted reliably, seeking to maximize the effects derived from positive factors and simultaneously minimize the negative factors [86].

According to [87], most decisions are made based on intuition and common sense. But more complex decisions require a more systematic approach and the adoption of appropriate decision support methodologies. Hence, complex decision problems require considering a plurality of points of view, technically called criteria concepts and multi--criteria methodologies.

Among the techniques that support the decision-making process AHP (Analytic Hierarchy Process) is one of the most frequently used [88], consisting of a multi-criteria analysis technique MCDM (Multiple Criteria Decision Making) that uses paired comparisons based on a numerical scale, systematizing and structuring the process [89, 90].

3.1.1 Decision Support Methods

Decision-making is a problem commonly faced by human beings, both in simple and complex tasks, which may be guided by single or multiple-choice parameters, and consists of collecting information, searching for potential alternatives and selecting these alternatives [91, 92]. Most of the practical interests require the global analysis of several attributes, in which a set of alternatives is associated with a set of criteria or attributes, and a set of consequences. So, the multi-criteria analysis aims to assist human beings' choices on the diversity of elements involved in a decision-making process, including uncertainty, convenience and antagonisms, among others [89, 13, 93].

There are two schools of decision analysis methods: Multi-Criteria Decision Making (MCDM), developed by the American school [94], and MCDA (Multi-Criteria Decision Analysis) created by the European school [95]. MCDM and MCDA are two approaches used to help decision-makers assess and compare alternative options when several competing objectives and criteria exist. MCDM and MCDA include the analysis and comparison of compromises between different criteria using mathematical and statistical tools to make informed decisions.

Nevertheless, there are some differences between MCDM and MCDA, which are generally associated with the American School of Thought and European School of Thought. One important difference is that the MCDM tends to focus more on quantitative methods and techniques, whereas the MCDA tends to focus more on qualitative methods and techniques. Another difference is that MCDM tends to focus more on data analysis and mathematical models to make decisions, whereas MCDA tends to focus more on expert judgment and decision-making processes in which stakeholders participate [96]. Additionally, MCDA's ultimate objective is to provide a collection of indicators to assist in decision-making rather than choosing solely a single index, as MCDM. A survey of techniques involving both methods can be found in [97, 98]. By the way, in this section, the American school MCDM will be addressed.

American School is known as compensatory since they have the function of aggregation or synthesis of information, through which the low performance of an alternative in a given criterion may be compensated by the high performance of this same alternative in another criterion [91, 92].

3.2 AHP Methodology Overview

In a complex environment, decision-making usually involves several criteria and alternatives, which may be tangible or intangible. To handle these qualitative and quantitative factors in MCDM, in the 1970s, Prof. Saaty [89, 13] proposed the AHP methodology, which provides a means of decomposing a complex problem into a hierarchy of sub-problems that may be more easily understood and subjectively evaluated.

For [89, 93], the AHP hierarchical analysis method may be understood as a general measurement theory that aims to support the decision-making process based on deductive and inductive thinking. It is eligible for both quantifiable and intangible criteria, ranging from planning to conflict resolution, guided by the knowledge and experience acquired. It was proposed to build the prioritization of each alternative based on the paired comparisons of each object with all the others. In this methodology, subjective ratings are converted into numerical values and processed to rank each alternative on a numerical scale [89].

AHP applies to both types of comparisons performed by humans: absolute comparison, in which alternatives are compared to a standard, whether existing in memory or developed through experience and relative comparison, when alternatives are compared to pairs according to a common attribute. So, by reducing complex decisions to a series of comparisons and then synthesizing the results, AHP helps turn subjective judgments into objective measures. For that means, AHP incorporates a useful technique to check the consistency of the decision maker's assessments, thus reducing bias in the decision-making process [99].

Due to its mathematical simplicity and flexibility, AHP has been the favourite decision tool for research in many fields, such as engineering [15], food [100], business[101], ecology [102], health [103, 104, 105] and government [106], for example.

3.2.1 Recommended Steps for Applying the AHP

AHP methodology, besically, requires the following steps: first, the development of the hierarchy (goal, criteria, and alternatives); second, assessing relative weights of the criteria; third, assessing the alternatives' relative priority concerning criteria and finally, calculating the global priorities [103]. These steps will be explained with a simple model, from [107], as an example.

- ☑ Develop a decision model: Divide the decision into a hierarchy of objectives (goal), criteria, and alternatives.

The hierarchy is structured with the problem goal at the top, the criteria and sub-criteria, if any, at the intermediate level, and finally, the alternatives for solving the problem at the bottom, as shown in Figure 3.1. So, structuring the decision problem as a hierarchy is fundamental to the AHP process [103]. By structuring the problem in this way, it is possible to better understand the decision to be achieved, the criteria to be used, and the alternatives to be evaluated.

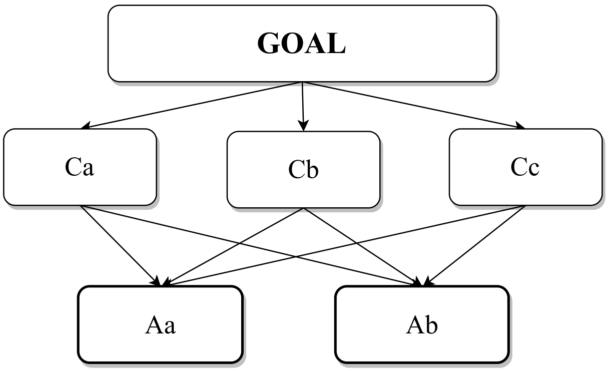


Figure 3.1 – AHP hierarchical structure

- ☑ Derive priorities (weights) for the criteria: The importance of criteria are compared pairwise with respect to the desired goal to derive their weights. It then checks the consistency of judgments; that is, a review of the judgments is done in order to ensure a reasonable level of consistency in terms of proportionality and transitivity.

The AHP model shown in Figure 3.1, C_a, C_b and C_c represent the criteria used to evaluate the alternatives. However, not all the criteria have the same importance for the decision-makers [103]. It could be that, for one specific institution C_c may have greater importance than C_b, or vice-verse. So, in AHP the criteria need to be compared pairwisely with respect to the goal to establish their relative importance, using an intensity scale developed for this purpose, as seen in Table 3.1.

Comparisons are made for each criterion/alternative and converted into quantitative numbers according to the Prof. Saaty fundamental scale presented in Table 3.2.

Table 3.1 – Pairwise comparison using the scale intesity of judment from Table 3.2

	C_a	C_b	C_c
C_a	1	c_{ab}	c_{ac}
C_b	$1/c_{ab}$	1	c_{bc}
C_c	$1/c_{ac}$	$1/c_{bc}$	1

where,

$$\begin{aligned} c_{ij} > 0 &\Rightarrow \text{positive} \\ c_{ii} = 1 &\Rightarrow c_{ji} = 1 \\ c_{ij} = {}^{1}\!/_{c_{ji}} &\Rightarrow \text{reciprocal} \\ c_{ik} = c_{ij} \times c_{jk} &\Rightarrow \text{consistency} \end{aligned}$$

Professor Saaty in [108] suggests that the priorities of one criterion or sub-criterion over another, or of one alternative over another, are established through pairwise comparisons, based on a single property at a time, so that the decision-maker, based on observation or experience, determines the relative importance among them, without concern for the influence of other properties or the importance of other elements. Thse consists of an information and communication tool of meanings that uses words to represent the concepts involved in the decisions, in this way, a semantic equivalent at each importance index.

Table 3.2 – The Saaty fundamental scale intensity

Scale of Saaty's Intensity		
Equal preference (importance)	1	1
Intermediate	2	1/2
Moderate preference (importance)	3	1/3
Intermediate	4	1/4
Strong preference (importance)	5	1/5
Intermediate	6	1/6
Very strong preference (importance)	7	1/7
Intermediate	8	1/8
Extreme preference (importance)	9	1/9

☑ Derive local priorities (preferences) for the alternatives: Derive priorities or the alternatives with respect to each criterion separately (following a similar process as in the previous step, i.e., compare the alternatives pairwise with respect to each criterion). Check and adjust the consistency as required.

This step consists of determining the relative importance (preferences) of each alternative based on each criterion. In other words, what are the priorities of the alternatives with respect to C_a, C_b, and C_c respectively? For this purpose, is done a pairwise comparison (using the numeric scale from Table 3.2) of all the alternatives, with respect to each criterion, included in the decision making model.

In a model with two alternatives, for example, it is required to make only one comparison (Alternative 1 with Alternative 2) for each criterion; a model with three alternatives would require to make three comparisons (Alternative 1 with Alternative 2, Alternative 2 with Alternative 3, and Alternative 1 with alternative 3) for each criterion; and so on. There will be as many alternative comparison matrices as there are criteria.

Therefore, up to this point have been obtained local priorities which indicate the preferred alternative with respect to each criterion. In this fourth step, there is need to calculate the gloal priority, also called final priority or model synthesis, for each alternative.

☑ Derive Global Priorities (Hierarchic Synthesis): All alternative priorities obtained are combined as a weighted sum, to take into account the weight of each criterion, to establish the overall priorities of the alternatives. The alternative with the highest overall priority constitutes the best choice.

At this point, the reader may feel a little intimidated by terms such as judgments, priorities, parwise comparison, consistency, etc.; however, details will clarify in Chapter 4.

3.2.2 Benefits and limitations of AHP

The Analytic Hierarchy Process (AHP) is a structured method for organizing and analyzing complex decision-making problems. It can be used to evaluate and compare multiple options or alternatives based on a set of predetermined criteria. Therefore, some benefits of using AHP include [109, 110, 111]:

☑ Structured approach: AHP provides a systematic and logical framework for decision-making, which helps to ensure that all relevant factors are considered, including intangibles such as experience, subjective preferences, and intuition, in a logical and structured way.

☑ Multiple criteria: AHP allows for the consideration of multiple criteria in the decision-making process rather than just a single criterion.

☑ Consistency: AHP helps to ensure consistency in decision-making by forcing the decision-maker to explicitly compare and evaluate the options against the criteria.

☑ Transparency: AHP can be used to document and communicate the decision-making process, making it more transparent to others.

However, AHP also has some limitations, including [112]:

☑ Expert judgment: AHP relies on expert judgment to determine the relative importance of different criteria and the relative performance of different options. This can be subjective and may introduce bias into the decision-making process.

☑ Complexity: AHP can be complex to implement, especially in situations with many criteria and options.

☑ Time: AHP can be time-consuming, as it requires the evaluation of many different pairwise comparisons.

☑ Limited data: AHP is not well-suited for situations where there is limited or incomplete data available.

4 Methodology Outline

Throughout the first chapter, the motivation and main objectives that justify the development of this work were presented. Hence, this chapter addresses the methodological aspects to achieve the proposed objectives thoroughly.

4.1 Materials and Methods

Due to the ease and high capacity of its mathematical resources, a computational algorithm has been developed based on the Matlab programming environment to calculate and parameterize the matrices and their consistency check, as it is a highly widespread and easy-to-understand platform from the user perspective. Hence, the methodology to achieve the proposed objectives follows the steps presented in Figure 4.1, with the respective details as follows.

Since this chapter handles the methodological aspects concerning the AHP method, it is essential to emphasize that for the hierarchy definition, exploratory research, through the literature review, was carried out, as presented in Chapter 2. Nevertheless, the problem structure, including the goal, the criteria, and alternatives in the hierarchy form, observing the elements of homogeneity assigned at each level, is presented in this section.

4.1.1 Define the Goal, the Criteria and Alternatives

A simple example centered on [107]'s work will be employed to clarify the methodology used in this work. The purpose of this example is to demonstrate the process of purchasing a new vehicle, which involves numerous factors, including cost, comfort, and safety. While various other elements could also be considered, this illustration will concentrate solely on these three requirements.

Multiple alternatives could be evaluated; however, for this example, it is assumed that only two options are under consideration: Car_1 and Car_2.

So, to analyze the decision of purchasing a car using the analytic hierarchy process, the following steps should be followed.

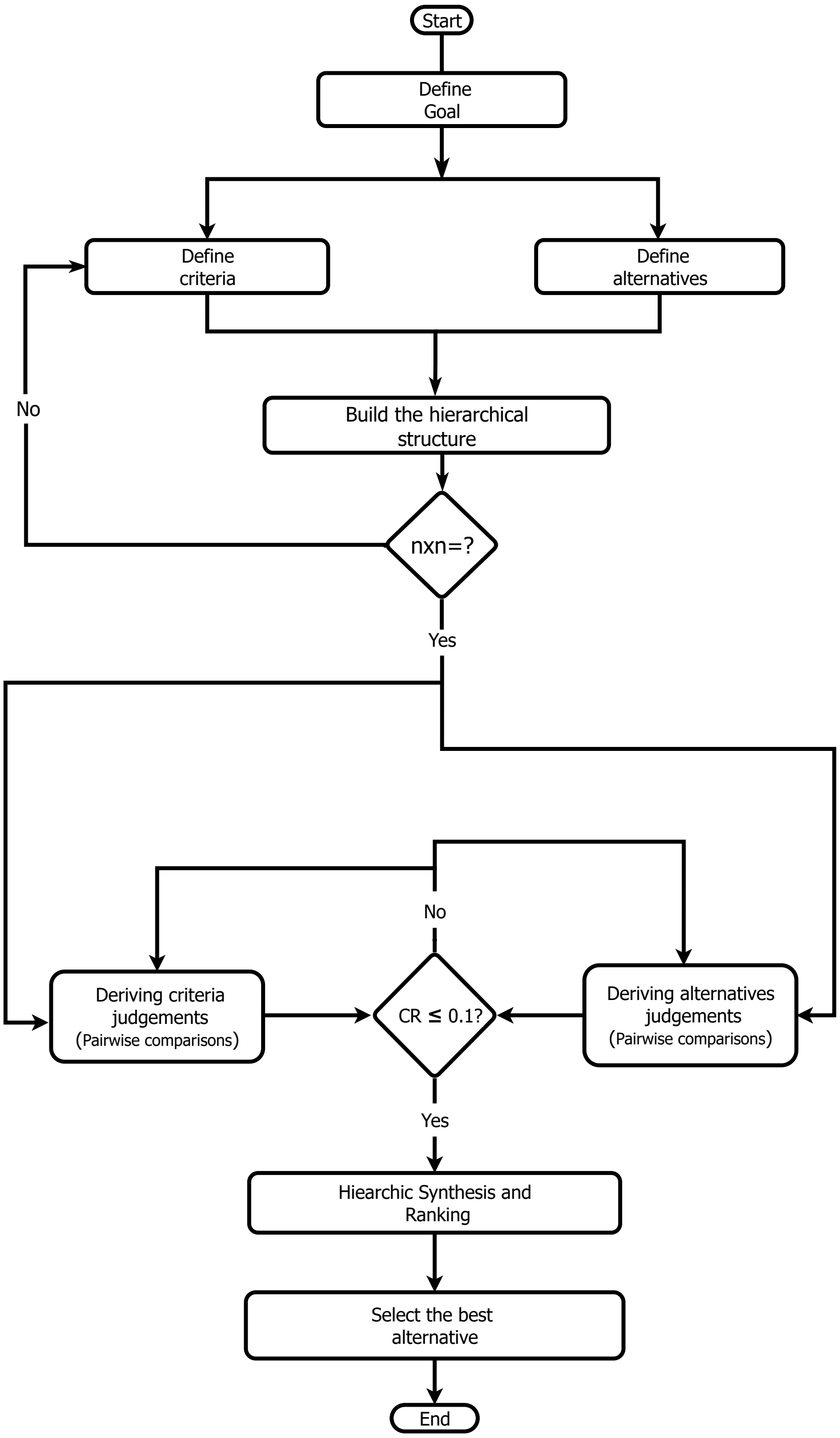


Figure 4.1 – Steps to apply the AHP methodology

4.1.2 Build the Hierarchical Structure

As previously stated in Chapter 3, the first step in an AHP analysis is to build a hierarchy for the decision. This is also called decision modeling consisting of building a hierarchy to analyze the decision.

Figure 4.2 illustrate the hierarchy for the proposed example. Note that the first level of the hierarchy is the goal; in this example, the purchase of a car. The second level of the hierarchy comprises the criteria to consider, namely cost, comfort, and safety. Lastly, the third level encompasses the available alternatives, which in this example are Car_1 and Car_2.

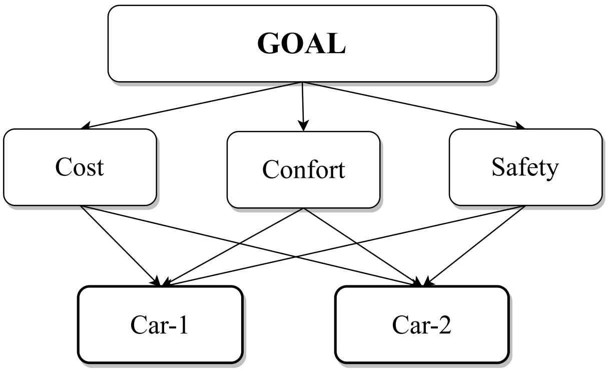


Figure 4.2 – Example of hierarchical structure

4.1.3 Deriving Priorities for the Criteria

The pairwise judgment matrices consist in determining the weights of the criteria concerning the objective, the criteria concerning the sub-criteria, if any, and the criteria concerning the alternatives. For this, ${}^{(n^2-n)}/_2$ judgments are needed for the nxn matrix, where n is the number of rows and columns.

To perform peer comparisons, the Saaty fundamental scale is used. Where usually, data are collected from experts or decision-makers corresponding to the hierarchical structure in pair-wise comparison of factors on a qualitative scale. So that, experts might classify the comparison as equal, marginally strong, strong, very strong, and extremely strong, as described in Table 3.2. The pairwise comparison for the proposed example requires the creation of a comparison matrix of the criteria involved in the decision, as shown in Table 4.1.

Table 4.1 – Pairwise comparison of criteria matrix with intensity judgments

	$Cost$	$Confort$	$Safety$
$Cost$	1	7	3
$Confort$	1/7	1	1/3
$Safety$	1/3	3	1

Cells in comparison matrices have recorded values from the numeric scale shown in Table 3.2 to reflect the relative preference in each of the compared pairs. Nevertheless, further details concerning how the author decided to assign the weights to criteria in Table 4.1 may be found in the author's work in [107].

Note in the comparison matrix of Table 4.1 that when the importance of a criterion is compared with itself; for example, cost versus cost, comfort versus comfort, or safety versus safety; the input value is 1 which corresponds to the intensity of equal importance in the scale of Table 3.2. This makes logical sense since the ratio of a given criterion's importance to its own importance will always be equal.

At this stage, it is becoming clear that one of the advantages of the AHP is its natural simplicity. According to [107], regardless of how many factors are involved in decision-making, the AHP method requires only the comparison of a pair of elements at any given time. Another significant advantage is that it allows the inclusion of tangible variables (e.g., cost) as well as intangible ones (e.g., comfort) as criteria in the decision.

So there is a need to calculate the criteria priorities using the approximate method that provides a valid approximation to the overall weights only when the comparison matrix has a very low inconsistency.

The approximate method requires normalizing the comparison matrix; that is done, first, by summing the values in each column, as shown in Table 4.2.

Table 4.2 – Column addition

	$Cost$	$Confort$	$Safety$
$Cost$	1	7	3
$Confort$	1/7	1	1/3
$Safety$	1/3	3	1
$\sum_{j=1}^{n} c_{ij}$	**1.476**	**11.000**	**4.333**

Next, divide each cell by the total of the column from Table 4.2, using the Equation (4.1).

$$W_{ij} = \frac{c_{ij}}{\sum_{j=1}^{n} c_{ij}} \tag{4.1}$$

The normalized matrix is shown in Table 4.3

Table 4.3 – Normalized matrix

	$Cost$	$Confort$	$Safety$
$Cost$	0.677	0.636	0.692
$Confort$	0.097	0.091	0.077
$Safety$	0.226	0.273	0.231

From this normalized matrix, obtain the final priorities (Table 4.4) by simply calculating the average value of each row using the Equation (4.2) (e.g., for the $Cost$ row:

$(\frac{(0.677+0.636+0.692)}{3} = 0.669))$.

$$\bar{W_c} = \frac{1}{n}\sum_{i=1}^{n} c_i \tag{4.2}$$

Where $\bar{W_c}$ is the matrix eigenector or priority vector; n is the matrix order; and c_i corresponds to each element inside the normalized matrix.

Table 4.4 – Calculation of priorities: row averages

	$Cost$	$Confort$	$Safety$	$\bar{W_c}$
$Cost$	0.677	0.636	0.692	**0.669**
$Confort$	0.097	0.091	0.077	**0.088**
$Safety$	0.226	0.273	0.231	**0.243**

According to the results in Table 4.4, it is clear that, for this example, its given more importance to the $Cost$ criterion (0.669), followed by $Safety$ (0.243). The $Confort$ criterion has a minimum weight (0.088) among the factors. In other word, criterion $Cost$ is the most important criterion with 66.9% of the total weight, followed by criterion $Safety$ with 24.3% and criterion $Confort$ with 8.8%, in that order.

4.1.4 Checking Consistency of Judgements

Since the numeric values are derived from the subjective preferences of individuals, it is impossible to avoid some inconsistencies in the final matrix of judgments. So, deriving criteria weights in AHP only makes sense if the comparison matrix is consistent or near consistent, and to assess this Prof. Saaty in [110] has proposed a calculation of CI (Consistency Index).

For this purpose, at the begining, the author proposed the use of the criteria priorities vector, calculated in Table 4.4. Multiply each value in the first column of the comparison matrix (Table 4.1) by the first criterion priority ($\bar{W_c}$) from Table 4.4; multiply each value in the second column by the second criterion priority; continue this process for all the columns of the comparison matrix (in this example, there are three columns). Then, add each calculated value to obtain a set of values, here named as λ_1, λ_2 and λ_3. Divide the elements (obtained in the previous steps) by the corresponding priority of each criterion as shown inEquation (4.3).

$$\lambda_1 = \frac{(0.669 \times 1) + (0.088 \times 7) + (0.243 \times 3)}{0.669} = 3.014$$

$$\lambda_2 = \frac{(0.669 \times \frac{1}{7}) + (0.088 \times 1) + (0.243 \times \frac{1}{3})}{0.088} = 3.002 \tag{4.3}$$

$$\lambda_3 = \frac{(0.669 \times \frac{1}{3}) + (0.088 \times 3) + (0.243 \times 1)}{0.243} = 3.005$$

Then, calculate the average of the values from the previous step; now such average value is called maxium eigenvalue λ_{max}, as shown in Equation (4.4).

$$\lambda_{max} = \frac{(3.014 + 3.002 + 3.005)}{3} = \mathbf{3.007} \tag{4.4}$$

Now is the time to calculate the CI (Consistency Index) as in Equation (4.5), where n is the number of compared elements (in our example n = 3).

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \tag{4.5}$$

$$= \frac{(3.007 - 3)}{(3 - 1)} = \mathbf{0.004}$$

CI is used to calculate CR (Consistency Ratio), defined as Equation (4.6):

$$CR = \frac{CI}{RI} < 0.1 \approx 10\% \tag{4.6}$$

$$= \frac{0.004}{0.58} = \mathbf{0.006}$$

Where RI (Random Index) is the average CI of 500 randomly filled matrices which are available in published tables [113, 110]; also summarized as seen Table 4.5. So that, CR less than 10 % means that the inconsistency is less than 10 % of 500 random matrices. CR values of 0.1 or less constitute acceptable consistency to continue the AHP analysis. However, if the CR is greater than 0.10, prof. Saaty [113], suggests revising the judgments to locate the cause of the inconsistency and correct it.

AHP calculates a consistency ratio (CR) comparing the consistency index (CI) of the matrix in question (the one with our judgments) versus the consistency index of a random-matrix (RI).

Table 4.5 – The random index RI [113, 110]

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

n is equivalent to the number of elements (criteria, sub-criteria, or alternatives) of the priority judgment matrix. Note that the CR calculation is unnecessary for matrices with up to two elements, as is seen in next section.

Hence, for the comparison matrix used in this example analysis, CR was found to be as 0.006, which constitutes an acceptable consistency and means that we can proceed to calculate the local priorities (weights) for the alternatives comparison matrices, as will be outlined in the next Section 4.1.5.

4.1.5 Deriving Local Priorities for the Alternatives

This section consists of determining the relative importance (preferences) of each alternative based on each criterion. In other words, what are the priorities of the alternatives with respect to $Cost$, $Confort$, and $Safety$ respectively? For this purpose, is done a pairwise comparison (using the numeric scale from Table 3.2) of all the alternatives, with respect to each criterion, included in the decision making model.

In a model with two alternatives, for example, it is required to make only one comparison (Alternative 1 with Alternative 2) for each criterion; a model with three alternatives would require to make three comparisons (Alternative 1 with Alternative 2, Alternative 2 with Alternative 3, and Alternative 1 with alternative 3) for each criterion; and so on. There will be as many alternative comparison matrices as there are criteria.

In this example, there is only two alternatives: Car_1 and Car_2 and there will be three criteria. This means that there will be three comparison matrices corresponding to the following three comparisons: With respect to the $Cost$ criterion: Compare Car_1 with Car_2. With respect to the $Confort$ criterion: Compare Car_1 with Car_2. With respect to the $Safety$ criterion: Compare Car_1 with Car_2.

In this example, its assumed to prefer very strongly (using the scale in Table 3.2) the alternative Car_1 over the alternative Car_2. This means that in the Car_1 - Car_2 alternative cell (i.e., the cell intersected by the row “Car_1” and the column “$Confort$”) of the comparison matrix regarding $Cost$ alternatives (Table 4.6), its assigned a value of 7 (value assigned using the scale from Table 3.2) to reflect the preference. Similarly, it is assigned the reciprocal reverse 1/7 in the Car_2 - Car_1 cell in the table.

Table 4.6 – Alternative comparison with respect to criterion $Cost$

	Car_1	Car_2
Car_1	1	7
Car_2	$1/7$	1
$\sum_{j=1}^{n} a_{ij}$	**1.143**	**8.000**

Normalize the matrix (using the Equation (4.1)) and averaging the rows (using the Equation (4.2)) to obtain the priorities (or $\bar{W_{a1}}$) for each of the alternatives (Table 4.7) with respect to criterion $Cost$.

Table 4.7 – Alternative preference with respect to criterion $Cost$

	Car$_1$	Car$_2$	$\bar{W}_{a1}$
Car$_1$	0.875	0.875	**0.0875**
Car$_2$	0.125	0.125	**0.125**

With respect to the criterion $Confort$, it was assumed that Car$_2$ is strongly preferred over the Car$_1$; that is, was assigned a value of 5 (using scale from Table 3.2) in the cell Car$_2$–Car$_1$ in our comparison matrix regarding $Confort$ alternative and the reciprocal reverse 1/5 in the Car$_1$–Car$_2$ cell (see Table 4.8)

Table 4.8 – Alternative comparison with respect to criterion $Confort$

	Car$_1$	Car$_2$
Car$_1$	1	⅕
Car$_2$	5	1
$\sum_{j=1}^{n} a_{ij}$	**6.000**	**1.200**

Normalize the matrix (using the Equation (4.1)) and averaging the rows (using the Equation (4.2)) to obtain the local priorities (or $\bar{W}_{a2}$) for each one of the alternatives with respect to criterion $Confort$. See Table 4.9.

Table 4.9 – alternative preference with respect to criterion $Confort$

	Car$_1$	Car$_2$	$\bar{W}_{a2}$
Car$_1$	0.167	0.167	**0.167**
Car$_2$	0.833	0.833	**0.833**

With respect to the $Safety$ criterion, the alternative Car$_1$ is extremely preferable to Car$_2$ with concering sunch criterion. These judgments are entered numerically (using scale from Table 3.1) in the respective cells in Table 4.10.

Table 4.10 – Alternative comparison with respect to criterion $Safety$

	Car$_1$	Car$_2$
Car$_1$	1	⅑
Car$_2$	9	1
$\sum_{j=1}^{n} a_{ij}$	**10.000**	**1.111**

Normalize the matrix (using the Equation (4.1)) and averaging the rows (using the Equation (4.2)) to obtain the local priorities (or $\bar{W}_{a3}$) for each one of the alternatives with respect to criterion $Safety$. See Table 4.11.

Table 4.11 – Alternative preference with respect to criterion $Safety$

	Car$_1$	Car$_2$	$\bar{W}_{a3}$
Car$_1$	0.100	0.100	**0.100**
Car$_2$	0.900	0.900	**0.900**

Notice that having only two alternatives to compare with respect to each criterion, simplifies the calculations with respect to consistency. Since there are only two elements to compare (in this example, Car$_1$ and Car$_2$), the respective comparison matrices will always be consistent (CR = 0). However, consistency must be checked if the number of elements pairwise compared is three or more, as will be seen in Chapter 6.

Up to this point have been obtained local priorities which indicate the preferred alternatives with respect to each criterion. In this fourth step, there is need to calculate the global priority, also called final priority or model synthesis, for each alternative.

4.1.6 Hierachic Systhesis and Ranking

The calculation of the global priority is made by using the local priority of each alternative ($\bar{W}_{a1}$, $\bar{W}_{a2}$, and $\bar{W}_{a3}$) calculated in Tables 4.7, 4.9 and 4.11, respectively. Next take into consideration the weights of each criteria ($\bar{W}_c$) from Table 4.4 and for this purpose they are inserted in the table as shown in Table 4.12.

In this example, the *Cost* criterion has a priority (or weight) of 0.669 and the alternative Car$_1$ has a local priority (or preference) of 0.875 relative to alternative Car$_1$; therefore, the weighted priority, with respect to *Cost* criterion, of the Car$_1$ alternative is: $0.669 \times 0.875 = 0.585$. A similar calculation was necessary to obtain the alternative Car$_1$ weighted priorities with respect to $Confort$ and $Safety$ criteria. The resulting matrix is shown in Table 4.13.

Table 4.12 – Local Priorities (or preferences) of the alternatives with respect to each criterion

	Cost	$Confort$	$Safety$
	0.669	***0.088***	***0.243***
Car$_1$	0.875	0.167	0.100
Car$_2$	0.125	0.833	0.900

Finally, the global priority of the Car$_1$ is obtained by the multiplication of the criteria weight ($\bar{W}_c$) by all the alternative weights ($\bar{W}_{a1}$, $\bar{W}_{a2}$, $\bar{W}_{a3}$) , summing up these results along the row, as Global priority = $\sum$ ($\bar{W}_{ai} \times \bar{W}_c$). This procedure is repeated for each of the alternatives being evaluated.

Table 4.13 – Calculation of global priorities

	$Cost$	$Confort$	$Safety$	Global Priority
	0.669	*0.088*	*0.243*	
Car_1	0.585	0.015	0.024	**0.624**
Car_2	0.084	0.074	0.219	**0.376**

The calculations for each alternative are shown below and the results are also presented.

Global Priority of the alternative Car_1: $0{:}875 \times 0.669 + 0.167 \times 0.088 + 0.100 \times 0.243 = 0.624$

Global Priority of the alternative Car_2: $0.125 \times 0.669 + 0.833 \times 0.088 + 0.900 \times 0.243 = 0.376$

In other words, given the importance (or weight) of each criteria ($Cost$, $Confort$, and $Safety$), the alternative Car_1 is preferable (with global priority of 62.4%) compared to the alternative Car_2 (with global priority of 37.6%).

4.2 Sensitivity Analysis

In the decision-making process, global priorities are strongly influenced by the weights given to the respective criteria. Therefore, performing a “what if” analysis is helpful to gauge how the final results would have changed if the criteria weights were different. This process is called sensitivity analysis [114].

Sensitivity analysis allows one to understand how robust the original decision is and what the factors are (i.e. which criteria influence the initial results). So, if the ranking does not change, the results are said to be robust; otherwise, they are sensitive. Therefore, it is an essential part of the process, and, in general, no final decision should be made without a sensitivity analysis [98]. For this, percentage changes will be made to the criteria weights and see how they change the global priorities of the alternatives.

5 Results and Findings

This chapter describes the results analysis of the collected data for the proposed research. As stated in Chapter 4, it aims to select the communication technology that best meets the HAN requirements for AMI applications in smart grid. For this purpose, a single case study has been defined to demonstrate the application of AHP methodology in a practical context. In addition, sensitivity analysis was performed, and all mathematical calculations were held in the MATLAB platform.

5.1 Communication Technology Selection for Smart Energy Metering Based on AHP Methodology - A Case Study

This section describes a case study on using the AHP methodology to select the best technology for metering purposes within HAN applications. The proposed case study is conducted based on the data sets from Table 2.2. From this, six communications requirements were considered as criteria, and four wireless communications technologies will be compared pairwisely as alternatives.

The standard house used in this case study follows the Brazilian Popular House, set out in Act No. 269 of 22nd March 2017, whose minimum basic criteria consist of an area of at least $36m^2$ if the service area is outside, or $39m^2$ if the service area is inside. Therefore, the solution intended to satisfy HAN applications with these characteristics has been defined as having a range area of $70m$; the least latency; a minimum data rate of $100kbps$; high reliability; high security; and interoperable.

However, it is important to emphasize that the requirements attributes defined in the proposed case study should be understood as having minimum values. Therefore, this means that the better a technology performs in any given requirement, the higher its score will be.

Thus, in addition, due to the high density of judgments required in AHP methodology applications, this section will be limited to defining and analyzing a single case study to demonstrate how the AHP can be useful in decision-making. However, the methodology can have its effectiveness tested by applying it in other scenarios of different magnitudes, using the Matlab code in Appendix A.

5.2 Define the Goal, the Criteria and Alternatives

As addressed above, common criteria were defined for the chosen alternatives, those that, according to the literature review (see Chapter 2), guarantee the essential requirements for communications in smart grid environment. However, both the criteria and alternatives definitions were held, and can be found in Chapter 4, considering wireless technologies.

☑ In this sense, there are six communication requirements to be taken into consideration, as criteria (C), namely: data rate (C_1), latency (C_2), security (C_3), range (C_4), reliability (C_5) and interoperability (C_6), see Figure 5.1:

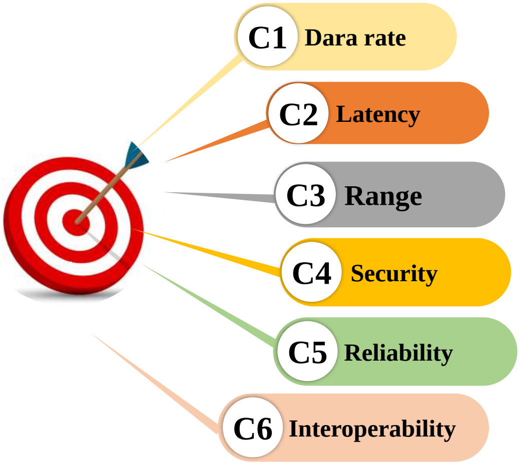


Figure 5.1 – Proposed criteria requirements

☑ With regard to alternatives (A), four (4) wireless technologies were considered, firstly, Wi-Fi (A_1), Z-Wave (A_2), ZigBee (A_3), and Bluetooth (A_4) for HAN applications (see Figure 5.2):

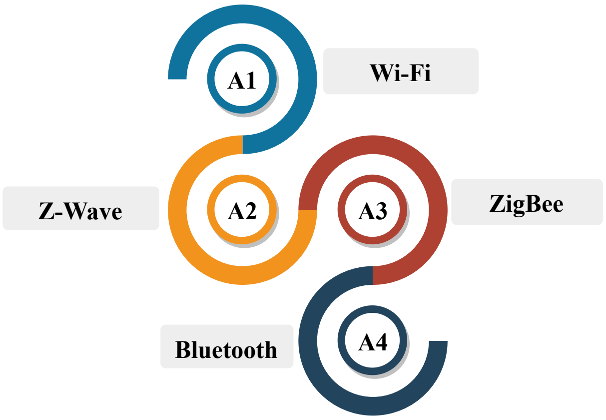


Figure 5.2 – Proposed alternatives for HAN applications

5.2.1 Build the Hierarchical Structure

Hierarchical structures constructions are held in Figure 5.3

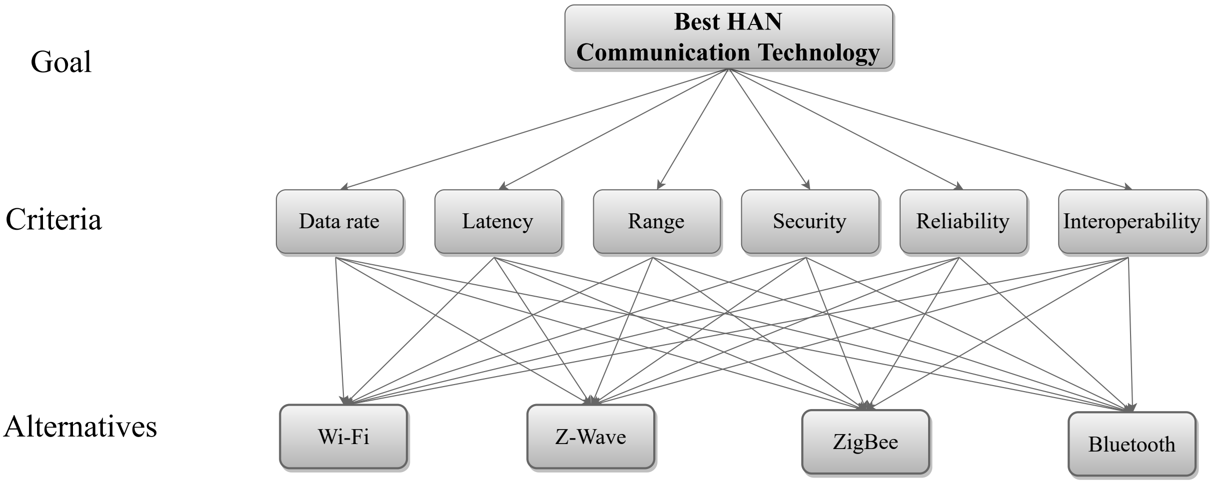


Figure 5.3 – Proposed hierarchical structure model for HAN applications

5.2.2 Deriving Priorities (Weights) for the Criteria

Since not all criteria are equally important for a specific purpose in time, the relative priorities (weights) for the criteria must be determined. Hence, it is called relative, as the weights for the obtained criteria are measured concerning each other, as shown below.

A matrix of the criteria involved in the decision was created to derive a pairwise comparison, as illustrated in Table 5.1. The cells of the comparison matrix received values of the numerical scale to reflect the intensity judgments of each comparison pair. So that, each element is compared to the other, the value assigned is considered to reflect the strength or weakness of one over the other, using the Saaty fundamental scale illustrated in Table 3.2.

5.2.2.1 Pairwise Comparison of Each Criterion with Respect to the Goal's Success

It is important to note that the transfer of valuable information through the Advanced Metering Infrastructure (AMI) has raised concerns about the privacy of individuals. Additionally, research in [33, 32] suggests that the need for robust infrastructure against failures and attacks, particularly for mission-critical applications like billing and grid control, highlights the importance of security as the top priority for most HAN applications.

Another view argued by [34] concerning the interoperability issue suggests that different appliances from different vendors are popular among households. Thus, interoperability is considered a critical requirement that must be attended to in the HAN environment. Hence, exchanging information amongst appliances and or meters is a technical imperative and the enabler of an innovative market.

1. **Comparison Question:** With respect to the goal's success, which criterion is important: $C3$(Range) or $C1$(Data rate)?

☑ It became clear that criteria $C3$(Range) and $C6$(Interoperability) are crucial to the goal's success. As a result, they were assigned the highest weights, 9 and 7, respectively, with one being considered much more important and the other very important than the other criteria. Therefore, the security ratio to the data rate's importance was assumed to be 9 ($C_3/C_1 = 9$), which means that the importance of the data rate relative to the importance of security is the reciprocal of this weight ($C_1/C_3 = 1/9$), as shown in the C_1 - C_3 comparison matrix in Table 5.1.

2. **Comparison Question:** With respect to the goal's success, which criterion is important: $C1$(Data rate) or $C6$(Intetroperability)?

☑ Likewise, the ratio of the importance of interoperability versus the importance of data rate was assumed as seven ($C_6/C_1 = 7$). This means that the opposite comparison, the importance of data rate relative to the importance of interoperability, yielded the reciprocal of this weight ($C_1/C_6 = 1/7$), as illustrated in the C_1 - C_6 comparison matrix in Table 5.1.

3. **Comparison Question:** With respect to the goal's success, which criterion is important: $C2$(Latency) or $C6$(Interoperability)?

☑ The relative importance of latency is not strict for HAN applications, as mentioned here; hence, the ratio of the importance of it versus the ratio of the importance of interoperability was assumed to be five times less important than the other, that is ($C_2/C_6 = 1/5$).

4. **Comparison Question:** With respect to the goal's success, which criterion is important: $C2$(Latency) or $C4$(Security)?

☑ Similarly, comparing the ratio of the importance of security versus the importance of latency, the weight was assumed as 2 ($C_4/C_2 = 2$) given the reason that security and latency both have intermediate importance for the goal's success, with a moderate preference for data security. Nevertheless, in the opposite comparison, the importance of latency relative to the importance of security yielded the reciprocal of the given weight ($C_2/C_4 = 1/2$).

5. **Comparison Question:** With respect to the goal's success, which criterion is more important: $C4$(Secrity) or $C5$(Reliability)?

☑ It was assumed that the ratio of the importance of range to the importance of both reliability and interoperability was equal as a result of our analysis. Therefore, it was considered equally important for the goal's success and was assigned a relative weight of one ($C4/C5 = 1$) and ($C4/C6 = 1$), as shown in Table 5.1.

Table 5.1 – Pairwise judgment matrices with respect to the goal's success

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	2	⅑	⅓	⅕	⅐
C_2	½	1	¼	⅓	⅓	⅕
C_3	9	4	1	2	1	2
C_4	3	3	½	1	1	1
C_5	5	3	1	1	1	1
C_6	7	5	½	1	1	1

6. **Comparison Question:** With respect to the goal's success, which criterion is important: $C1$(Data rate) or $C2$(Latency)?

Furthermore, it is mentioned in [37] that latency refers to the length of time it takes for a packet of data to move from one point on the network to another, while for [41], data rate refers to the quantity of data communicated within a certain period via a network.

Additionally, the goal of HAN is to enable communication between various home appliances and smart meters [43, 42]. Whose usual latency needs for metering applications are in the order of seconds and whose primary operational requirements are tiny amounts of the data rate of up to $100kbps$ [41].

In [25, 26], the authors suggest that data rate and latency are both important, but neither is strictly more important than the other. Meter readings typically require less than 100 kbps and are sent periodically every 15 minutes daily, indicating that a balance between the two is necessary.

☑ Mathematically, it is assumed that the ratio of the importance of data rate versus the importance of latency is two ($C_1/C_2 = 2$). Moreover, due to this, the opposite comparison, the importance of latency relative to the importance of data rate, yielded the reciprocal of this value, one over two ($C_2/C_1 = 1/2$), as illustrated in C_2 - C_1 comparison matrix in Table 5.1.

7. **Comparison Question:** With respect to the goal's success, which criterion is important: $C1$(Data rate) or $C4$(Security)?

As addressed in Chapter 2, the HAN environment is directly related to the end consumer. These networks are deployed indoors and require short-range and low communication rates. They use technologies that offer a data rate of up to $100kbps$ and cover a distance of approximately $100m$ [115].

Considering that the average range of the smart meter in HAN is about $15m$ [116], it is pretty evident that the range may be moderately more important than the data rate. Furthermore, obstructions like walls and doors can decrease the range when the meter is far from the home display unit. So, technologies with much range of capabilities are suggested for this application.

☑ Therefore, the ratio of the importance of range versus the importance of data rate is assumed to be three ($C_4/C_1 = 3$). This means that the opposite comparison, the importance of data rate relative to the importance of range, resulted from the reciprocal of this weight, one over three ($C_1/C_4 = 1/3$), as shown in the C_1 - C_4 comparison matrix in Table 5.1.

8. **Comparison Question:** With respect to the goal's success, which criterion is more important: $C4$(Security) or $C2$(Latency)?

☑ Likely, it is assumed that the ratio of range importance to latency importance was a weight of three ($C4/C2 = 3$), Which states that C_4 is moderately more important than latency in the HAN environment. This means that the opposite comparison, the importance of latency relative to the importance of range, yielded the reciprocal of this value, one over three ($C_2/C_4 = 1/3$), as seen in Table 5.1.

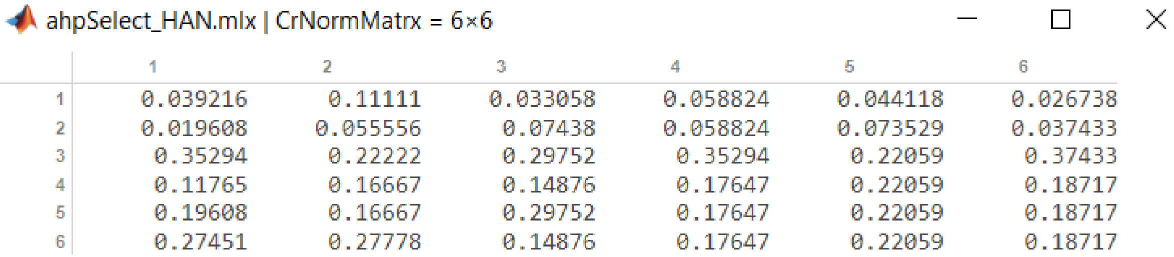
9. **Comparison Question:** With respect to the goal's success, which criterion is more important: $C1$(Data rate) or $C5$(Reliability)?

According to [32], reliability is one of the most concerning issues in communications for the smart grid, especially in the HAN domain, where the smart meter data are collected. As seen in Table 2.1, for metering purposes, reliability must be above 99.0% since the communications across this interface will affect the overall customer experience and may impact the value of these services.

☑ For instance, it became clear that the ratio of the importance of reliability versus the importance of data rate is five ($C_5/C_1 = 5$). Nevertheless, the opposite comparison, the importance of data rate relative to the importance of reliability, resulted from the reciprocal of this weight, one over five (C_1/C_5 = ⅕), as shown in the C_5 - C_1 comparison matrix in Table 5.1. So, this means that C_5 appears to be strongly more important than the data rate.

5.2.2.2 Checking Consistency of Criteria Judgments

To ensure consistency in judgments, several steps must be taken. First, after the judgment matrices have been completed for each criterion, normalizations are performed by dividing each matrix element by the sum of the values in the corresponding column, including the element's value itself, as each criterion holds the same level of importance. To achieve this, Equation (4.1) is implemented in Matlab, resulting in the matrix shown in Figure 5.4. The index from 1 to 6 seen in the matrix corresponds to the criteria from one to six, as listed in Table 5.1.

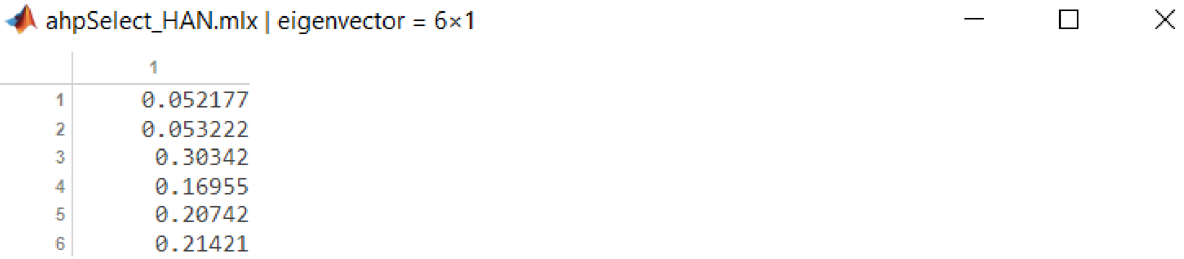


ahpSelect_HAN.mlx | CrNormMatrx = 6×6

	1	2	3	4	5	6
1	0.039216	0.11111	0.033058	0.058824	0.044118	0.026738
2	0.019608	0.055556	0.07438	0.058824	0.073529	0.037433
3	0.35294	0.22222	0.29752	0.35294	0.22059	0.37433
4	0.11765	0.16667	0.14876	0.17647	0.22059	0.18717
5	0.19608	0.16667	0.29752	0.17647	0.22059	0.18717
6	0.27451	0.27778	0.14876	0.17647	0.22059	0.18717

Figure 5.4 – Normalized comparison matrix

Secondly, with the normalized matrix, a criteria's priority vector was calculated using an arithmetic average of each criterion value. Each element of the normalized criteria matrix is summed per row and divided by the number of elements, according to Equation (4.2). The result is also considered the matrix eigenvector, shown in Figure 5.5.



ahpSelect_HAN.mlx | eigenvector = 6×1

```
        1
1   0.052177
2   0.053222
3    0.30342
4    0.16955
5    0.20742
6    0.21421
```

Figure 5.5 – Criteria comparison matrix priority vector

Figure 5.6 illustrates the importance degree of each criterion for the goal's success. As can be seen, the criteria C_3 had the greatest weight with C_3 of 30,3% of the total importance. Yet the C_6 criterion, whose weight indicates a degree of importance of 21.4%, has the second greater weight. Furthermore, C_5 weighted 20.74%, meaning that it is the third great importance among all judged criteria. The fourth criterion(Security) with great weight is C_4 with 16.95% of importance. In comparison the less important criteria C_1(Data rate) and C_2(Latency) obtained very close weights of 5.21% and 5.32% of importance, respectively.

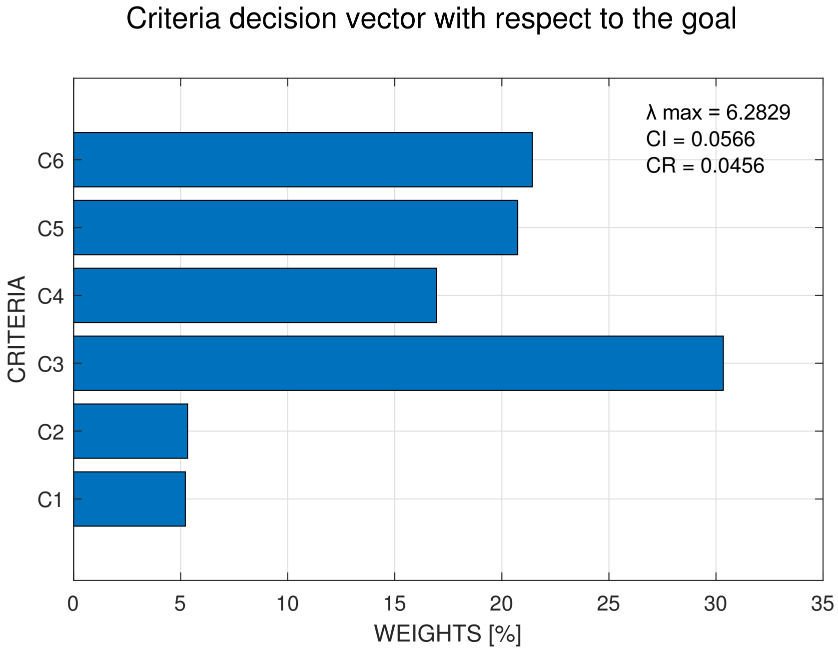


Figure 5.6 – Ranking of the degree of criteria importance for the goal's success

AHP calculates a consistency ratio CR by comparing the consistency index CI of the matrix with the judgments made with the random consistency index RI, see Table 4.5. As can be confirmed in Table 5.1, the matrix under judgment is of an order of $6x6$; that is, it has six criteria that, when compared pairwisely, the maximum inconsistency allowed, according to Table 4.5, is 1.24.

It was used the judgment matrix and priority vector to check the consistency rate. First, it was multiplied the values in each column of the comparison matrix Table 5.1 by the corresponding priority in Figure 5.5 vector. Then, it was calculated the weighted sum of each row. Finally, it was divided the weighted sum vector elements by each criterion's corresponding priority.

Furthermore, a weighted sum of the values in each row was performed. Then, the elements of the weighted sum vector (obtained in the previous step) were divided by the corresponding priority of each criterion. The average of the values of the previous step was then calculated, obtaining a value called eigenvalue, and symbolized as λ_{max}.

From these, was possible to obtain $\lambda_{max} = 6.2829$, CI=0.05657, and CR $= 0.04562 < 0.1$ as illustrated in Figure 5.6. Therefore, this indicates that the matrix can be considered consistent, according to Equation (4.6) in [113, 110].

5.2.3 Deriving Local Priorities for the Alternatives with respect to the Criteria

This section determines each alternative's importance for each criterion (data rate, latency, range, security, reliability, and interoperability). These rankings are specific to each criterion and are called local priorities. There will be used these rankings to calculate global priorities later.

For this purpose, it was used the same process as used for the criteria relative judgment. It was also compared the alternatives against each other with respect to each criterion and assigned weights based on their performance. It was combined data from Table 2.2 to make these comparisons and give higher weights to alternatives with better properties for achieving the goal.

5.2.3.1 Pairwise comparisons of alternatives with respect to $C1$(Data rate)

1. **Comparison Question:** With respect to the data rate criterion (C_1), which alternative is preferable: $A1$(Wi-Fi) or $A2$(Z-Wae)?

Analyzing Table 2.2, and comparing Wi-Fi and Z-Wave technologies concerning data rate, it can be observed that Wi-Fi possesses better performance in terms of data rate capacity of $150Mbps$ over $100kbps$ of Z-Wave. Nevertheless, Wi-Fi is a trendy technology in the HAN environment.

☑ Therefore, the ratio of the importance of Wi-Fi versus the importance of Z-wave was assumed to be 7 ($A_1/A_2 = 7$), meaning that the opposite comparison, the importance of Z-wave relative to the importance of Wi-Fi, yielded the reciprocal of this weight ($A_2/A_1 = 1/7$), see Table 5.2. Furthermore, the weight was chosen because Wi-Fi has more data transmission capability than Z-Wave, as illustrated in Table 2.2. Therefore, one alternative is much more important than the other.

Table 5.2 – Pairwise judgment matrices with respect to the data rate

	A_1	A_2	A_3	A_4
A_1	1	7	5	4
A_2	⅐	1	½	¼
A_3	⅕	2	1	⅓
A_4	¼	4	3	1

2. **Comparison Question:** With respect to the data rate criterion (C_1), which alternative is preferable: $A1$ (Wi-Fi) or $A3$(ZigBee)?

☑ Likewise, the ratio of the importance of Wi-Fi versus the importance of ZigBee is five ($A_1/A_3 = 5$). The motivation for this value can be seen in Table 2.2; the data transmission capability of Wi-Fi is relatively higher than the ZigBee (150 Mbps > 250 kbps). Notwithstanding the opposite comparison, the importance of ZigBee relative to the importance of Wi-Fi yielded the reciprocal of this value (A_3/A_1 = ⅕).

3. **Comparison Question:** With respect to the data rate criterion (C_1), which alternative is preferable: $A1$(Wi-Fi) or $A4$(Bluetooth)?

☑ Another comparison concerning the ratio of the importance of Wi-Fi versus the importance of Bluetooth has been judged to be of four (A_1/A_4= 4). The comparison deserved such weight because, looking at Table 2.2, Wi-Fi is moderately much more important than Bluetooth (150 Mbps > 1 Mbps). In the opposite comparison, the importance of Bluetooth relative to the importance of Wi-Fi yielded the reciprocal of this value (A_4/A_1 = ¼).

4. **Comparison Question:** With respect to the data rate criterion (C_1), which alternative is preferable: $A2$(Z-Wae) or $A3$(ZigBee)?

Even though Z-Wave and ZigBee are wireless protocols thought and designed for home automation. The practical measurement of their data transmission capabilities depends on a few factors, such as frequency. ZigBee's higher frequency (2.4GHz) allows it to transmit more data but reduces the signal range. On the other hand, Z-wave with a frequency of 908MHZ reduces the data transmission capacity [40, 56]. In this approach, therefore, neither the frequency nor the range of these technologies will be taken accountably. But, yes, their nominal values of data rate.

☑ So, given that ZigBee has a moderately higher data rate capability (250 kbps) than Z-wave (100 kbps), according to Table 2.2, in our judgment, it has been considered that, for HAN applications, ZigBee might be two times more important than Z-Wave ($A_3/A_2 = 2$). This means that the opposite comparison, the importance of Z-Wave relative to the importance of ZigBee, yielded the reciprocal of the given weight ($A_2/A_3 = ½$).

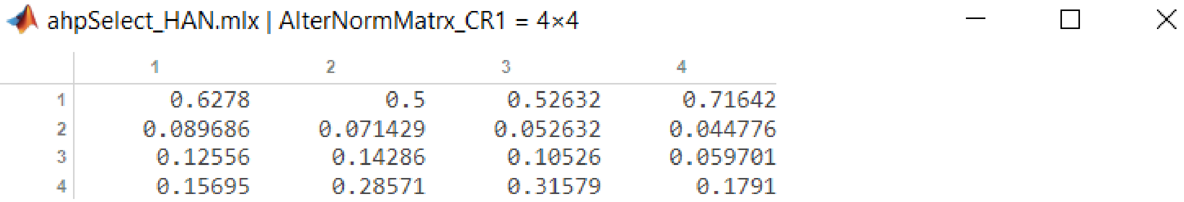
5. **Comparison Question:** With respect to the data rate criterion (C_1), which alternative is preferable: $A2$(Z-Wae) or $A4$(Bluetooth)?

Regarding Bluetooth's importance ratio versus Z-Wave's importance ratio concerning data rate, Table 2.2 can be used. It can be seen that Bluetooth is characterized by a data rate capacity of about $1Mbps$, while ZigBee, as mentioned earlier, has a data rate of $250kbps$. This highlights the preference for Bluetooth for HAN applications' potentiality.

☑ Therefore, the comparison of the degree of importance of Z-Wave versus the degree of the importance of Bluetooth with respect to data rate capability was defined as four ($A_4/A_2 = 4$). This means that the opposite comparison, the importance of Bluetooth relative to the importance of Z-Wave, yielded the reciprocal of the given weight ($A_2/A_4 = ¼$), as shown in Table 5.2.

5.2.3.2 Checking Consistency of Alternatives Judgments with Respect to C_1

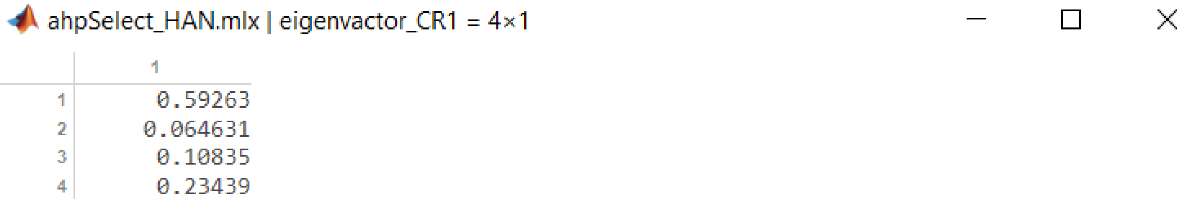
To check the consistency of the comparison matrix for the alternatives with respect to data rate, the same procedures as in Section 5.2.2.2 were applied. Figure 5.7 represents the alternatives normalized matrix with respect to the first criteria (Data rate, which has been named as C_1). This was carried out so that an eigenvector could be defined for matrix comparisons, as shown in Figure 5.8.



```
ahpSelect_HAN.mlx | AlterNormMatrx_CR1 = 4×4

          1           2           3           4
1      0.6278         0.5     0.52632     0.71642
2    0.089686    0.071429    0.052632    0.044776
3     0.12556     0.14286     0.10526    0.059701
4     0.15695     0.28571     0.31579      0.1791
```

Figure 5.7 – Normalized comparison matrix with respect to the Data rate



ahpSelect_HAN.mlx | eigenvactor_CR1 = 4×1

```
        1
1    0.59263
2   0.064631
3    0.10835
4    0.23439
```

Figure 5.8 – Alternatives' comparison matrix priority vector

Figure 5.9, combined with Figure 5.8, show the importance degree of each alternative with respect to the C_1. So, considering the data rate capabilities of the alternatives, the ranking demonstrates that the Wi-Fi has scored $A_1 = 0{,}5926$ of weight, corresponding to 59,26% of preference amongst the evaluated alternatives. Consecutively, Bluetooth has had $A_4 = 23.43\%$ of preference for its data transmission capacity. ZigBee showed $A_3 = 10.83\%$ of scores, while Z-Wave obtained a weight of $A_2 = 0.0646$ (6.46%) of application potentiality.

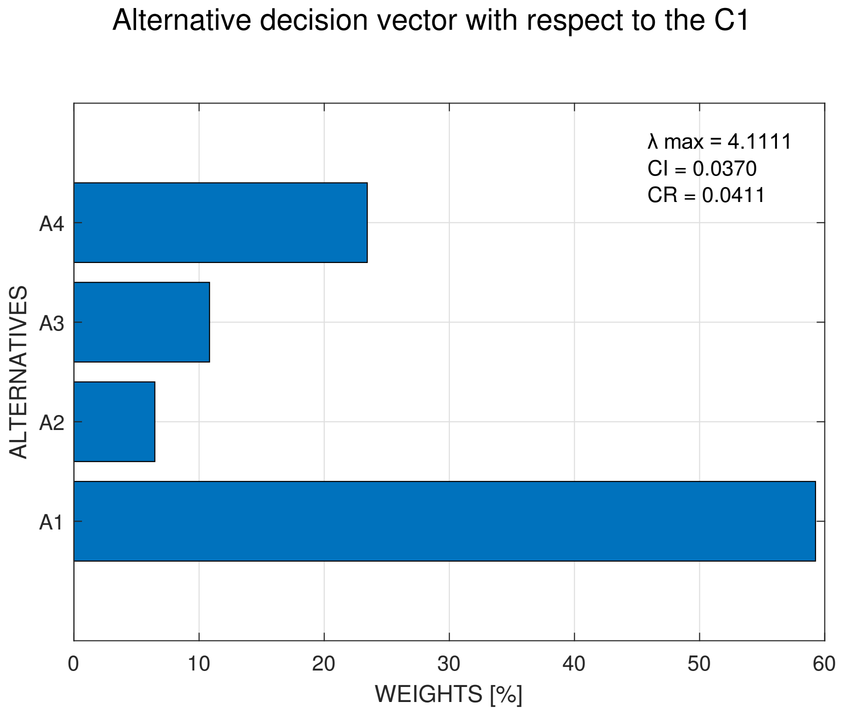


Figure 5.9 – Ranking of the degree of alternatives' importance with respect to data rate criterion

In addition, according to [110], the matrix comparison was considered to have an acceptable rate consistency, hence with an eigenvalue of $\lambda_{max} = 4.1111$, consistency index $CI = 0.037019$ and $CR = 0.04132$ ($4.132\% < 10\%$) demonstrate respecting transitivity rule, as illustrated in Figure 5.9.

5.2.3.3 Pairwise comparisons of alternatives with respect to $C2$ (Latency)

1. **Comparison Question:** With respect to the latency criterion (C_2), which alternative is preferable: $A1$(Data rate) or $A2$(Z-Wave)?

Even though, according to [41], for HAN applications, AMI can tolerate higher network delays because most smart meters send their readings periodically every 15 minutes per day; this comparison was prioritized. Therefore, the alternatives with the lowest latency got higher weights.

So, comparing Wi-Fi and Z-Wave technologies concerning latency, it can be observed that Wi-Fi has a higher latency capacity of $150ms$ over $100ms$ than Z-Wave, which means that Z-Wave possesses better performance in terms of latency compared to Wi-Fi.

☑ Therefore, the comparison of the degree of importance of Z-Wave versus the degree of the importance of Wi-Fi with respect to latency capability has been defined as one over two ($A_1/A_2 = 2$). This means that the opposite comparison, the importance of Wi-Fi relative to the importance of Z-Wave, yielded the reciprocal of the given weight ($A_2/A_1 =$ ½); that is, Z-Wave and Wi-Fi have intermediate importance among each other.

Table 5.3 – Pairwise judgment matrices with respect to the latency

	A_1	A_2	A_3	A_4
A_1	1	½	⅕	4
A_2	2	1	½	6
A_3	5	2	1	7
A_4	¼	⅙	⅐	1

2. **Comparison Question:** With respect to the latency criterion (C_2), which alternative is preferable: $A2$(Z-Wave) or $A4$(Bluetooth)?

A comparative analysis was carried out regarding the degree of importance between Z-Wave and Bluetooth. In this case, according to Table 2.2, the Z-Wave latency capability, as mentioned above, is $100ms$, which is much less than the Bluetooth latency capability of $34s$. This means that Z-Wave has an intermediate position of preference between strongly more important and very much more critical than Bluetooth, see Table 3.2.

☑ Therefore, the comparison of the degree of importance of Z-Wave versus the degree of the importance of Bluetooth with respect to latency capability has been defined to assume one over two ($\mathrm{A}_2/\mathrm{A}_4 = 6$). This means that the opposite comparison, the importance of Bluetooth relative to the importance of Z-Wave, yielded the reciprocal of the given weight ($\mathrm{A}_4/\mathrm{A}_2$ = ⅙).

3. **Comparison Question:** With respect to the latency criterion (C_2), which alternative is preferable: $A2$(Z-Wave) or $A3$(ZigBbee)?

Likewise, analyzing the Table 2.2, it can be observed that the ZigBee alternative presents a latency capacity of $15ms$ in opposition to $100ms$ presented by the Z-Wave alternative.

☑ Therefore, the ratio of the importance of ZigBee versus the importance of Z-Wave with respect to the latency can obtain the weight of two ($\mathrm{A}_3/\mathrm{A}_2 = 2$). This means that the opposite comparison, the importance of Z-Wave relative to the importance of ZigBee, yielded the reciprocal of this value, one over 2 ($\mathrm{A}_2/\mathrm{A}_3$ = ½), as seen in Table 5.3.

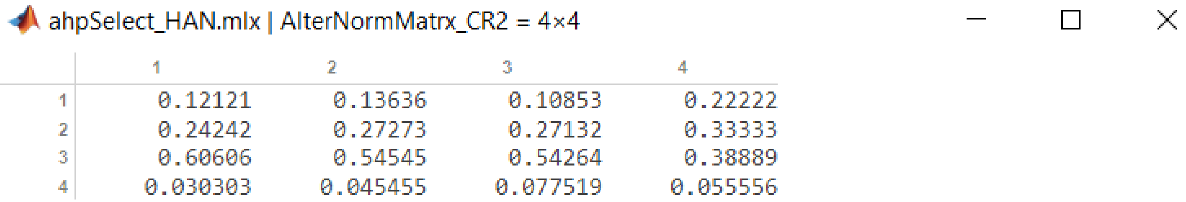
4. **Comparison Question:** With respect to the latency criterion (C_2), which alternative is preferable: $A3$(ZigBee) or $A4$(Bluetooth)?

The same analysis can be carried out concerning performance comparison between ZigBee and Bluetooth. As evident from the above mention, ZigBee with $15ms$ latency time is much more preferable than Bluetooth with $34s$ latency.

☑ So, the ratio of the importance of ZigBee versus the importance of Bluetooth with respect to the latency was weighted to be as ($\mathrm{A}_3/\mathrm{A}_4 = 7$). This means that the opposite comparison, the importance of Bluetooth relative to the importance of ZigBee, yielded the reciprocal of this value, one over seven ($\mathrm{A}_4/\mathrm{A}_3$ = ⅐), as seen in Table 5.3.

5.2.3.4 Checking Consistency of Alternatives Judgments with Respect to C_2 (Latency)

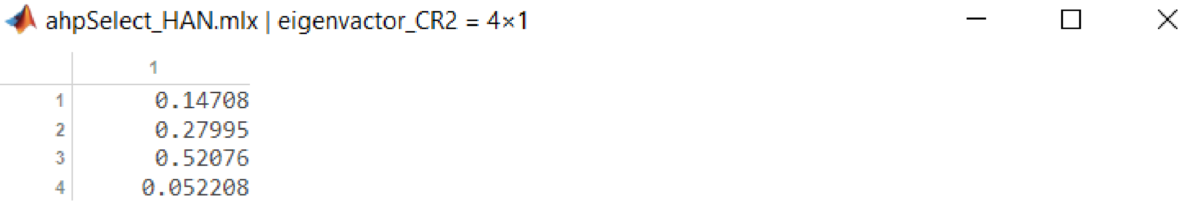
Figure 5.10 represents the normalized matrix of the comparison of the alternatives with respect to the latency criterion. Normalization is an important step in the AHP as it allows pairwise comparisons to be used to make decisions and rank the alternatives in a consistent and meaningful way, eliminating biases and ensuring that the relative importance or performance of the alternatives with respect to particular criterion is accurately reflected in the matrix of priorities, as stated in [99].



ahpSelect_HAN.mlx | AlterNormMatrx_CR2 = 4×4

	1	2	3	4
1	0.12121	0.13636	0.10853	0.22222
2	0.24242	0.27273	0.27132	0.33333
3	0.60606	0.54545	0.54264	0.38889
4	0.030303	0.045455	0.077519	0.055556

Figure 5.10 – Normalized comparison matrix with respect to the latency criterion



ahpSelect_HAN.mlx | eigenvactor_CR2 = 4×1

	1
1	0.14708
2	0.27995
3	0.52076
4	0.052208

Figure 5.11 – Alternatives comparison matrix priority vector

Figure 5.11 illustrates the ranking degree of each alternative concerning the latency criterion. ZigBee technology was the winning alternative, with an A_3 of 52.076% of preference. Nevertheless, the second winning alternative was Z-Wave with at least A_2 of 27.995% of weight; In addition, Wi-Fi earned about 14.708% of potentiality to fulfill the goal. Finally, the Bluetooth alternative got the least preference amongst the alternative comparison matrix, with a C_4 of 5.2208%. Furthermore, as expected, the comparison matrix can be considered consistent since the consistency ratio is 3.630, as seen in Figure 5.12.

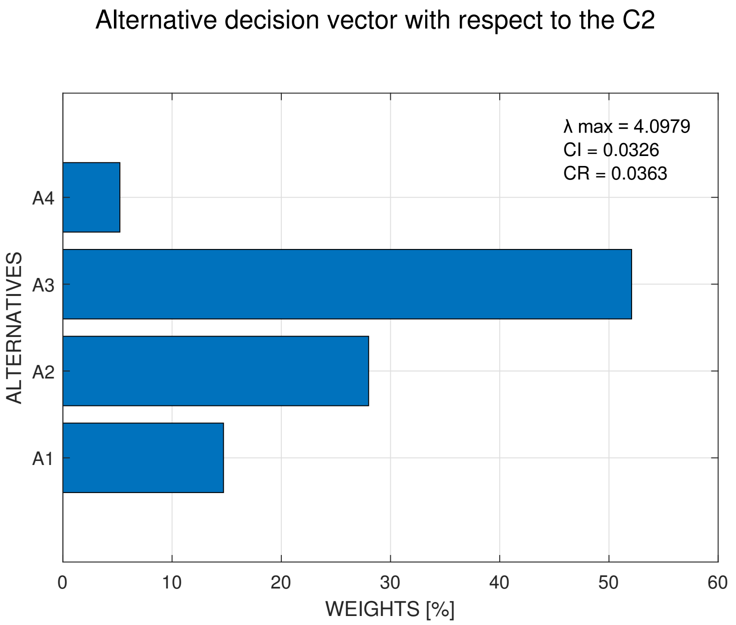


Figure 5.12 – Ranking of the degree of alternatives' importance with respect to the latency criterion

5.2.3.5 Pairwise comparisons of alternatives with respect to $C3$(Range)

1. **Comparison Question:** With respect to the security criterion (C_3), which alternative is preferable?

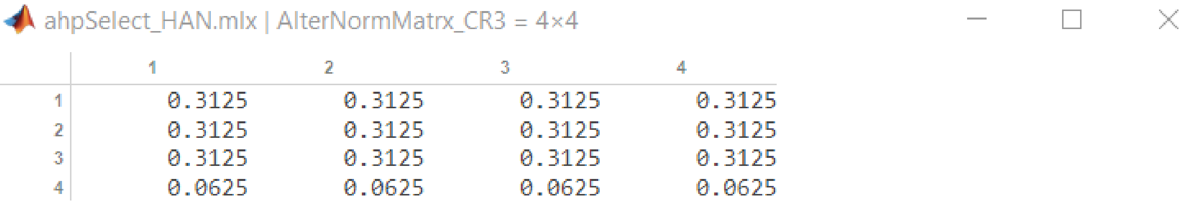
Despite being considered secure [53], in this study, it has not been possible to quantify the inherent security of each communication technology for HAN applications, which would enable an equal comparison among the alternatives. Therefore, for simulation purposes, it was assumed that almost all technologies have equal weight except for Bluetooth, which according to the literature review, it has a minor security capability. So, the majority of alternatives were considered to be five times more preferable than Bluetooth. So these alternatives were assigned equal weight, as proposed by professor Saaty in Table 3.2; see Table 5.4.

Table 5.4 – Pairwise judgment matrices with respect to the security criterion

	A_1	A_2	A_3	A_4
A_1	1	1	1	5
A_2	1	1	1	5
A_3	1	1	1	5
A_4	1/5	1/5	1/5	1

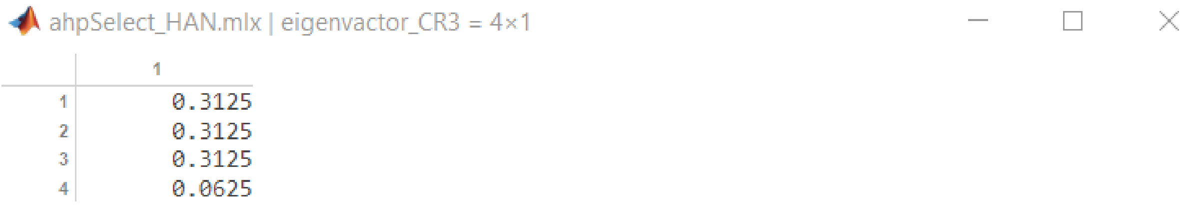
5.2.3.6 Checking Consistency of Alternatives Judgments with Respect to C_3(Range)

As a result of the assumptions made above, the A_1 up to A_3 alternatives contribute to achieving the goal, with a degree of importance of 31.25%; nevertheless, A_4 was the least preferable relative alternative. Furthermore, the matrix comparison was considered to be absolute with a CR of 0, as illustrated in Figure 5.14 and Figure 5.15.


ahpSelect_HAN.mlx | AlterNormMatrx_CR3 = 4×4

```
        1          2          3          4
1    0.3125     0.3125     0.3125     0.3125
2    0.3125     0.3125     0.3125     0.3125
3    0.3125     0.3125     0.3125     0.3125
4    0.0625     0.0625     0.0625     0.0625
```

Figure 5.13 – Normalized comparison matrix with respect to security criterion



ahpSelect_HAN.mlx | eigenvactor_CR3 = 4×1

```
        1
1   0.3125
2   0.3125
3   0.3125
4   0.0625
```

Figure 5.14 – Alternatives' comparisons matrix priority vector

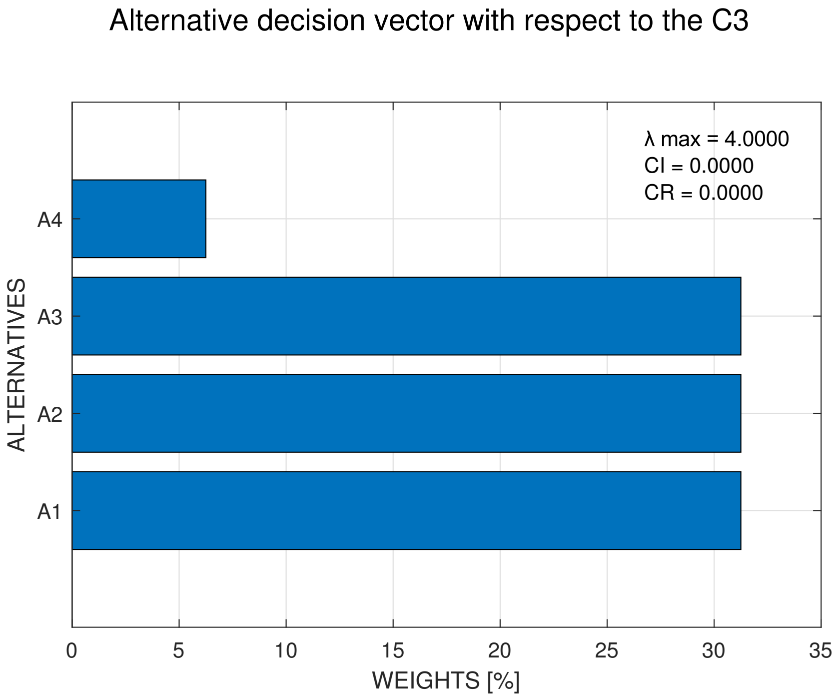


Figure 5.15 – Ranking of the degree of alternatives' importance with respect to security criterion

5.2.3.7 Pairwise comparisons of alternatives with respect to $C4$(Security)

1. **Comparison Question:** With respect to the range criterion (C_4), which alternative is preferable: $A1$(Wi-Fi) or $A2$(Z-Wave)?

According to the literature review in [25, 26], applications in a HAN environment generally require a low range. However, considering environments with obstacles such as walls, it is desirable to have alternative technologies capable of providing the best range. Therefore, technology alternatives with these characteristics will be assigned high-importance weights.

Table 5.5 – Pairwise judgment matrix with respect to the range

	A_1	A_2	A_3	A_4
A_1	1	3	3	5
A_2	⅓	1	1	3
A_3	⅓	1	1	3
A_4	⅕	⅓	⅓	1

So, comparing Wi-Fi and Z-Wave technologies concerning range, there can be observed that Wi-Fi has a higher range capacity of up to $300m$ versus $100m$ of Z-Wave. This means that Wi-Fi performs better in terms of range compared to Z-Wave.

☑ Therefore, the ratio of the importance of Wi-Fi versus the importance of Z-Wave is three (A_1/A_2=3). Moreover, due to this, the opposite comparison, the importance of Z-Wave relative to the importance of Wi-Fi, yielded the reciprocal of this value, one over three ($A_2/A_1 = ⅓$), as illustrated in Table 5.5.

2. **Comparison Question:** With respect to the range criterion (C_4), which alternative is preferable: $A1$(Wi-Fi) or $A3$(ZigBee)?

The same analysis was considered regarding the relative importance between Wi-Fi and ZigBee. Such that the ratio of the importance of Wi-Fi versus the importance of ZigBee is three (A_1/A_3=3). Moreover, due to this, the opposite comparison, the importance of ZigBee relative to the importance of Wi-Fi, yielded the reciprocal of this value, one over three ($A_3/A_1 = ⅓$), as illustrated in Table 5.5.

3. **Comparison Question:** With respect to the range criterion (C_4), which alternative is preferable: $A1$(Wi-Fi) or $A4$(Bluetooth)?

Another relative comparison is regarding Wi-Fi and Bluetooth. As seen in Table 2.2, Bluetooth has a range of up to $10m$, making it a less preferred technology for this application.

☑ In this sense, the ratio of the importance of Wi-Fi versus the importance of Bluetooth is three ($A_1/A_4 = 5$). Nevertheless, the opposite comparison, the importance of Bluetooth relative to the importance of Wi-Fi, yielded the reciprocal of this value, one over five ($A_4/A_1 = ⅕$).

4. **Comparison Question:** With respect to the range criterion (C_4), which alternative is preferable: $A2$(Z-Wave) or $A4$(Bluetooth)?

Comparing the technological alternative between Z-Wave and Bluetooth, one has that Z-Wave, on the one hand, has greater range capability with range of up to $100m$, whereas Bluetooth, on the other hand, with range of up to $10m$, with low capability, as mentioned earlier.

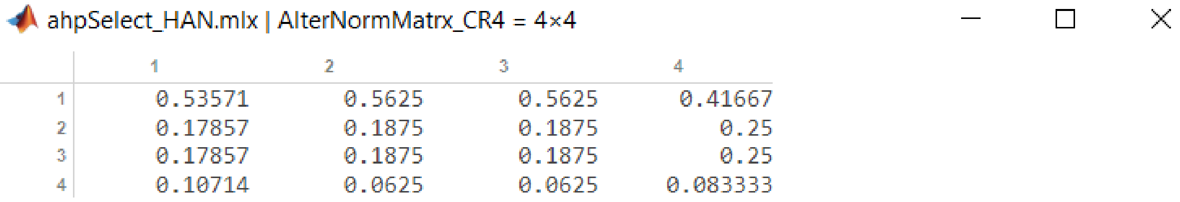
☑ Therefore, the ratio of the importance of Z-Wave versus the importance of Bluetooth is four ($A_2/A_4 = 3$). While the opposite comparison, the importance of Bluetooth relative to the importance of Z-Wave, yielded the reciprocal of this value, one over four ($A_4/A_2 =$ ⅓).

5. **Comparison Question:** With respect to the range criterion (C_4), which alternative is preferable: $A3$(ZigBee) or $A4$(Bluetooth)?

☑ These analyses were extended to compare the relative importance of the ZigBee and Bluetooth alternatives. So, the ratio of the importance of ZigBee versus the importance of Bluetooth is three ($A_3/A_4 = 3$). Whereas the opposite comparison, the importance of Bluetooth relative to the importance of ZigBee, yielded the reciprocal of this value, one over two ($A_4/A_3 =$ ⅓).

5.2.3.8 Checking Consistency of Alternatives Judgments with Respect to C_4(Security)

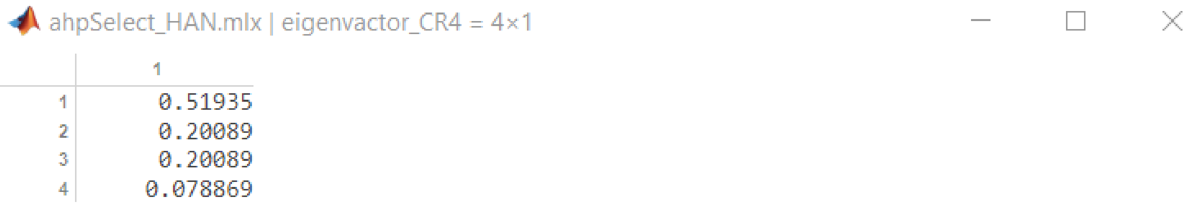
Figure 5.16 shows the alternative normalized matrix with respect to the range criterion (C_4). The purpose of doing so was to obtain the matrix eigenvector represented by Figure 5.17 and get the ranking relative alternatives.



ahpSelect_HAN.mlx | AlterNormMatrx_CR4 = 4×4

	1	2	3	4
1	0.53571	0.5625	0.5625	0.41667
2	0.17857	0.1875	0.1875	0.25
3	0.17857	0.1875	0.1875	0.25
4	0.10714	0.0625	0.0625	0.083333

Figure 5.16 – Normalized comparison matrix with respect to range criterion



```
ahpSelect_HAN.mlx | eigenvactor_CR4 = 4×1
        1
1   0.51935
2   0.20089
3   0.20089
4  0.078869
```

Figure 5.17 – Alternatives comparisons matrix priority vector

According to the data presented in Figures 5.17 and 5.18, Wi-Fi was the top choice for range in a HAN, with 51.535% preference. Z-wave and ZigBee were the second most adherent alternatives at 20.089%, and Bluetooth was the least favored with 7.8869% preference.

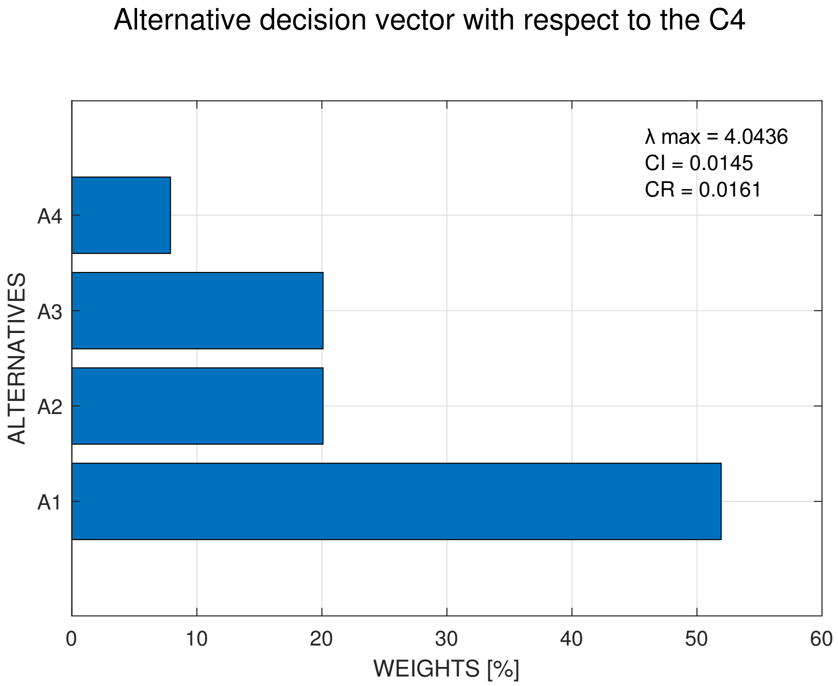


Figure 5.18 – Ranking of the degree of the importance of alternatives with respect to the range criterion

5.2.3.9 Pairwise comparisons of alternatives with respect to $C5$(Reliability)

1. **Comparison Question:** With respect to the reliability criterion (C_5), which alternative is preferable?

For [117], the success of the grid system depends upon the customer's need, measured as reliability. It is also emphasized in [118], stating that if there is poor reliability, there may often occur a reduction in the demand, utilization, and social benefit of electricity.

In this regard, Wi-Fi and Bluetooth were assumed to have medium and poor reliability capacities, respectively, according to Table 2.2. These presumptions are driven by the fact that, on the one hand, these technologies are unlicensed [48]. Moreover, these technologies also fall under star networks, in which each connected device converses alone and directly with a central switch. On the other hand, mesh networks like ZigBee and Z-Wave do not need those devices directly connect with a central gateway. Instead, a mesh network enables each device to act as a repeater, sending the signal to other devices in this way. Additionally, these are licensed technologies.

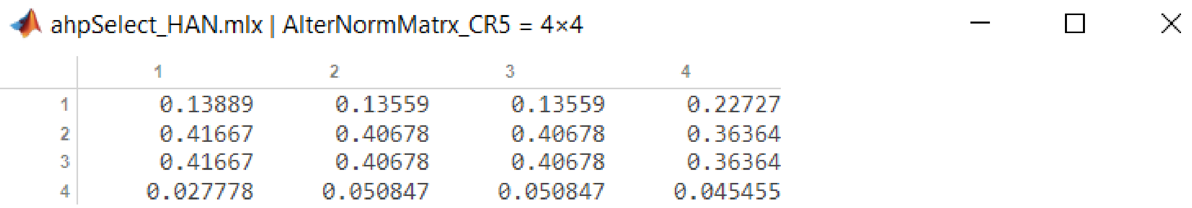
☑ Therefore, the judgment input for the matrix comparison was assumed to be as $A_1/A_4 = 5$, meaning that Wi-Fi is five times more preferable than Bluetooth, concerning reliability. In addition, $A_2/A_1 = 3$, so as $A_3/A_1 = 3$, which means that Wi-Fi is ⅓ times less than both Z-Wave and ZigBee technologies. Besides, $A_2/A_4 = 8$, and $A_3/A_4 = 8$, meaning that Bluetooth is ⅛ times less than both Z-Wave and ZigBee, see Table 5.6.

Table 5.6 – Pairwise judgment matrices with respect to the reliability

	A_1	A_2	A_3	A_4
A_1	1	⅓	⅓	5
A_2	3	1	1	8
A_3	3	1	1	8
A_4	⅕	⅛	⅛	1

5.2.3.10 Checking Consistency of Alternatives Judgments with Respect to C_5(Reliability)

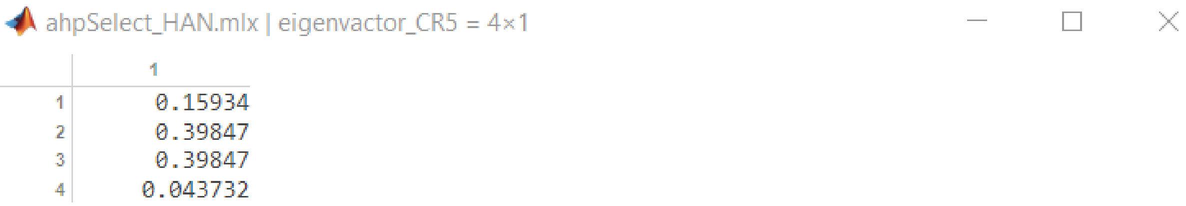
Figure 5.19 illustrates the alternatives normalized matrix concerning the reliability criterion (C_5). In addition, Figures 5.20 and 5.21 show the local importance of each alternative, ranking each of them in terms of their importance to the objective criterion.



ahpSelect_HAN.mlx | AlterNormMatrx_CR5 = 4×4

```
          1          2          3          4
1   0.13889    0.13559    0.13559    0.22727
2   0.41667    0.40678    0.40678    0.36364
3   0.41667    0.40678    0.40678    0.36364
4  0.027778   0.050847   0.050847   0.045455
```

Figure 5.19 – Normalized comparison matrix with respect to reliability criterion



```
      1
1     0.15934
2     0.39847
3     0.39847
4    0.043732
```

Figure 5.20 – Alternatives comparisons matrix priority vector

As seen in Figure 5.21, ZigBee and Z-Wave were the local winning alternatives, with 39,847% of importance. Besides, Wi-Fi and Bluetooth have shown 15,934% and 4,3732% of importance, respectively. It should be noted that the consistency ratio of the matrix is considered acceptable since it is CR = 0.018643 < 0.1.

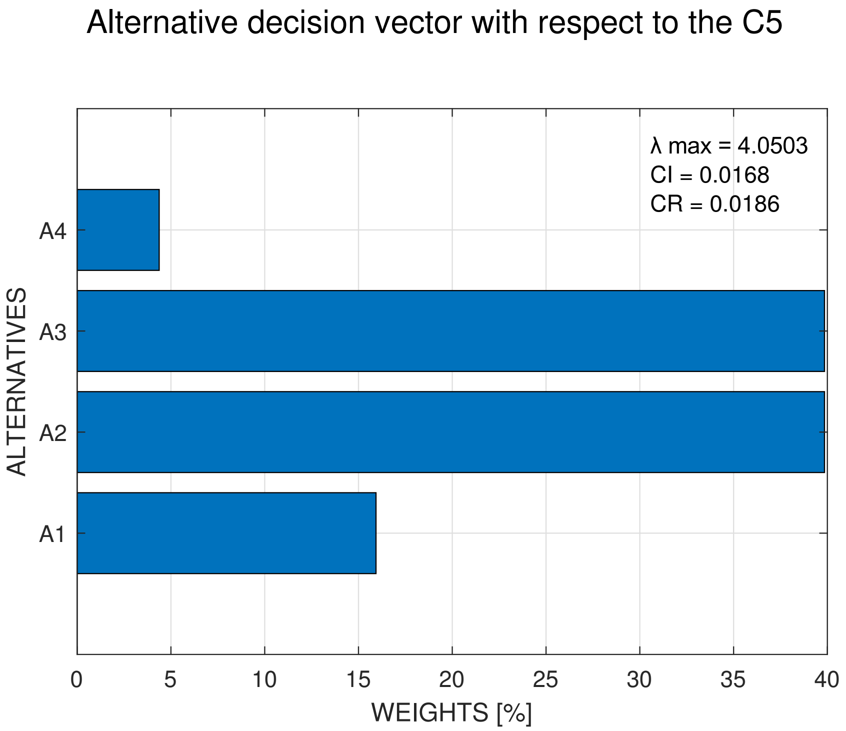


Figure 5.21 – Ranking of the degree of alternatives' importance with respect to the reliability criterion

5.2.3.11 Pairwise comparisons of alternatives with respect to $C6$(Interoperability)

1. **Comparison Question:** With respect to the interoperability criterion (C_6), which alternative is preferable?

It is important to note that the technology's interoperability may depend on the specific devices and systems in use and the specific implementation of the technology. So, in general, technologies must be interoperable so that they may be used to share data with a wide range of devices from different vendors.

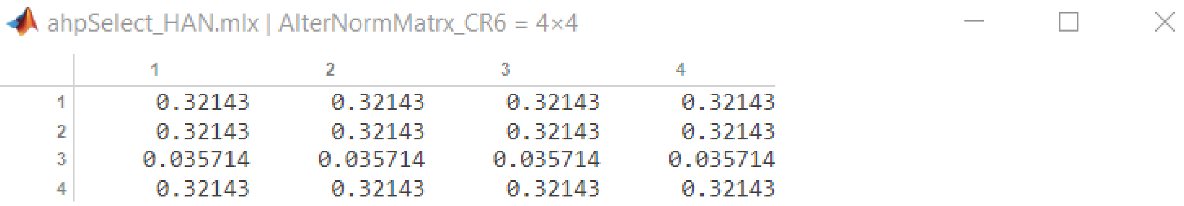
Therefore, for the simulation purposes, all the alternatives' comparisons were assigned to assume equal weights, as 1, except for ZigBee, which has data share capability with other brands. As stated in Table 3.2, meaning that in such a situation, both alternatives contribute equally to the goal's success, see Table 5.7.

Table 5.7 – Pairwise judgment matrices with respect to the interoperability criterion

	A_1	A_2	A_3	A_4
A_1	1	1	9	1
A_2	1	1	9	1
A_3	⅑	⅑	1	⅑
A_4	1	1	9	1

5.2.3.12 Checking Consistency of Alternatives Judgments with Respect to C_6(Interoperability)

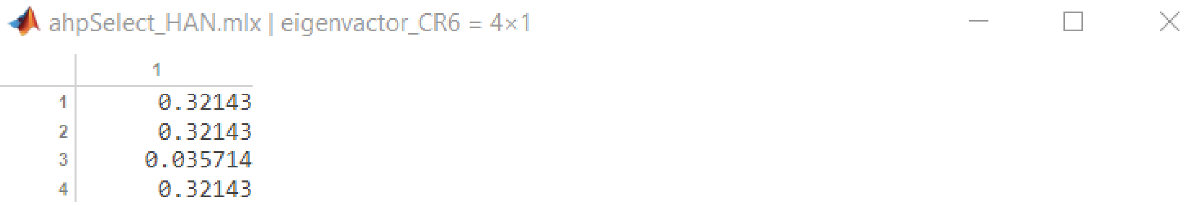
As usual, Figure 5.22 represents the normalized matrix. Figure 5.23 represents the eigenvector of the matrix local priorities, schematized in Figure 5.24, which shows the tie in preference of 32,14%, in average, except for Zigbee with 3,57% as expected.



ahpSelect_HAN.mlx | AlterNormMatrx_CR6 = 4×4

```
           1          2          3          4
1     0.32143    0.32143    0.32143    0.32143
2     0.32143    0.32143    0.32143    0.32143
3    0.035714   0.035714   0.035714   0.035714
4     0.32143    0.32143    0.32143    0.32143
```

Figure 5.22 – Normalized comparison matrix with respect to interoperability criterion



ahpSelect_HAN.mlx | eigenvactor_CR6 = 4×1

```
           1
1     0.32143
2     0.32143
3    0.035714
4     0.32143
```

Figure 5.23 – Alternatives comparisons matrix priority vector

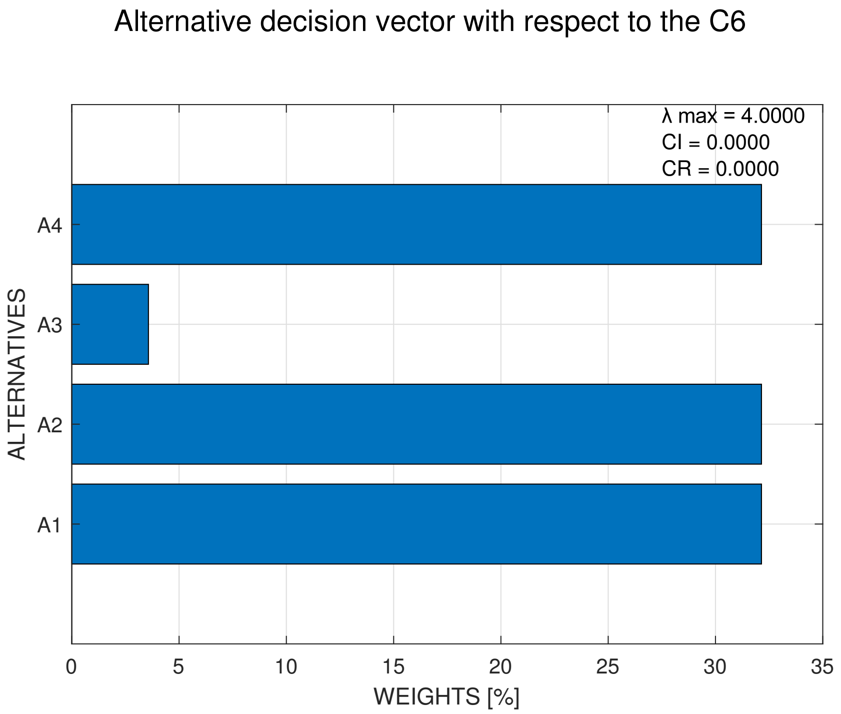


Figure 5.24 – Ranking of the degree of alternatives' importance with respect to the interoperability criterion

5.2.4 Hierarchic Synthesis and Ranking

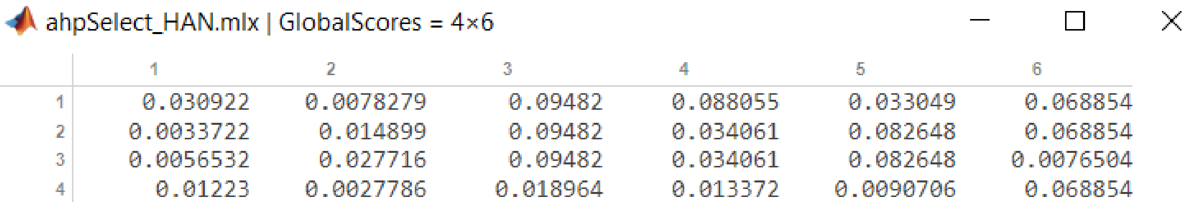
Table 5.8 represents the matrix resulting from the clustering of the eigenvectors from the alternatives comparison matrix with respect to each criterion (as shown in Figures 5.8, 5.11, 5.14, 5.17, 5.20 and 5.23) with the eigenvector from the criteria comparison matrix with respect to the goal success (Figure 5.5). The values of the eigenvector from the alternatives comparison matrix are illustrated in the brown color, while the values of the eigenvector from the criteria comparison matrix are illustrated in the blue color.

The eigenvector of the criteria weight for each value was multiplied by the score for each criterion for each alternative. This can be seen in Figure 5.25. The resulting values were then added together for each alternative to create an overall score, as shown in figure Figure 5.26.

Note that the criteria data rate and latency have had almost the same low weights as the weights of other criteria, as seen in Table 5.8. Hence, it is evident that their influences would be minor for the objective. However, even so, these criteria had high scores relative to the Wi-Fi and ZigBee alternatives since they demonstrated better performance in terms of capacity in these aspects.

Table 5.8 – Clustering of local priorities of alternatives versus the eigenvector of the criteria

		Criteria eigenvector					
		Data rate	Latency	Security	Range	Reliability	Interoper.
		0.052177	0.053222	0.30342	0.16955	0.20742	0.21421
Alternatives	Wi-Fi	0.59263	0.14708	0.3125	0.51935	0.15934	0.32143
	Z-Wave	0.064631	0.27995	0.3125	0.20089	0.39847	0.32143
	ZigBee	0.10835	0.52076	0.3125	0.20089	0.39847	0.035714
	Bluetooth	0.23439	0.052208	0.0625	0.078869	0.043732	0.32143



```
ahpSelect_HAN.mlx | GlobalScores = 4×6

            1           2           3           4           5           6
1    0.030922   0.0078279     0.09482    0.088055    0.033049    0.068854
2   0.0033722    0.014899     0.09482    0.034061    0.082648    0.068854
3   0.0056532    0.027716     0.09482    0.034061    0.082648   0.0076504
4     0.01223   0.0027786    0.018964    0.013372   0.0090706    0.068854
```

Figure 5.25 – Correlation of the criteria's eigenvector with the alternatives' eigenvector

Based on the calculations obtained from the criteria pair comparison matrix, security and interoperability criteria were the most important in making decisions, followed by reliability and range requirements, latency and data rates as shown in Figure 5.5. Therefore, it can be concluded that since it is about communication technology in a HAN environment, these criteria guided the decision to select an alternative that would exert a preponderant influence on the final decision presented in Figure 5.27.

Different options were evaluated (different topologies of wireless technology) by comparing them to a set of criteria to determine their overall “quality” or adherence to a specific goal. Then, there was prioritized the alternatives based on the results. In this case, Wi-Fi (A_1) technology had a 32.353% adherence to the goal, as it performed well on specific criteria such as data rate, range, and the importance of specific requirements for communication within a HAN (Home Area Network) environment. These results are presented in Table 5.8.

Furthermore, the Z-Wave (A_2) technology alternative showed an adherence of 29.865%. This was due to its performance with respect to the criteria such as latency (0.27995), range (0.20089), reliability (0.39847), and of course, security (0.3125) and interoperability (0.32143).

```
ahpSelect_HAN.mlx | GlobalScores = 4×1
        1
1    0.32353
2    0.29865
3    0.25255
4    0.12527
```

Figure 5.26 – Global priorities with respect to the criteria eigenvector

For the third alternative winner, ZigBee (A_3) was adherent in 25.255%; however, since it got less performance, especially in one of the critical requirements listed above, such as the interoperability criterion (0.035714), justified by its limitation in this requirement as stated by [54].

In conclusion, the option with the lowest adherence to the goal was alternative four, which is Bluetooth (A_4) technology. Despite performing well on the interoperability criterion, it was negatively impacted by poor performance on other criteria, resulting in a fourth-place of 12.527% of score, as presented in Figure 5.27.

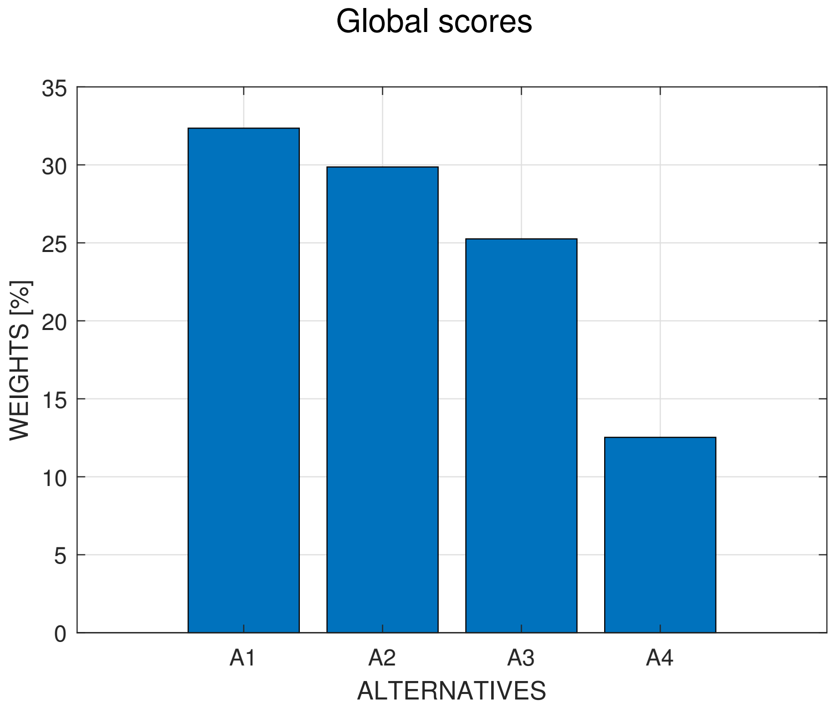


Figure 5.27 – Ranking of global priorities

Therefore, analyzing the data characteristics of the technologies under consideration concerning their performance, as discussed in Chapter 2, there can be concluded that, although this is a hypothetical case study, the result presented here corroborates with the reality shown in the market. According to the research conducted in [58], statistically, Wi-Fi has been amongst the most widely used technology for applications in HAN environments worldwide, with about 30% of penetration. This is due to the combination of different performance criteria that give an advantage to the preference for this technology, especially for residential applications.

5.3 Sensitivity Analysis

In this section, sensitivity analyses are carried out for each criterion. For this, percentage variations from 0 to 100 were simulated to assess each criterion's influence in the decision vector, mainly when varying its weight concerning all other criteria.

Table 5.9 shows that when the weight of the data rate criterion is 5.5218%, the winning alternative is Wi-Fi technology, with 32.353% of adherence, continuing as winner even with the percentage increase in weight, as shown in Figure 5.28. This is an expected trend since Wi-Fi has the highest data rate capacity among the analyzed technologies.

This trend is also observable from the dotted vertical line (break-even point), above 50% of weight increase concerning Bluetooth technology, which, according to Table 2.2, has the second highest data transmission capacity among the analyzed technologies.

Table 5.9 – Data rate criterion(C_1) variation

ΔC_1	**Wi-Fi**	**Z-Wave**	**ZigBee**	**Bluetooth**
0%	0,3087	0,3115	0,2605	0,1193
10%	0,3371	0,2868	0,2453	0,1308
20%	0,3655	0,2622	0,2301	0,1423
30%	0,3939	0,2375	0,2148	0,1538
40%	0,4223	0,2128	0,1996	0,1653
50%	0,4507	0,1881	0,1844	0,1768
60%	0,4791	0,1634	0,1692	0,1883
70%	0,5075	0,1387	0,1540	0,1999
80%	0,5358	0,1140	0,1388	0,2114
90%	0,5642	0,0893	0,1236	0,2229
100%	0,59263	0,06463	0,108350	0,23439
0,05218	32,353%	29,865%	25,255%	12,527%

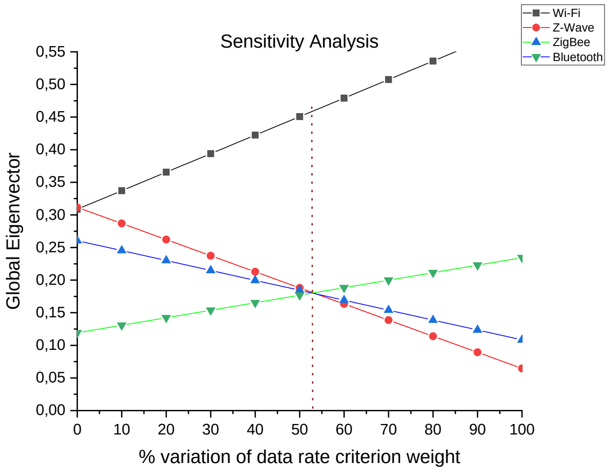


Figure 5.28 – Data rate criterion sensitivity

From the break-even point, with about 20% increase in the weight of the latency criterion, the Wi-Fi technology loses the preference, as the winning alternative, in favor of the ZigBee technology, which, according to the data in Table 2.2, it is about 15*ms* in opposition to 100*ms* and 150*ms* from the alternatives Z-Wave and Wi-Fi, respectively, as shown in Table 5.10 and Figure 5.29.

Table 5.10 – Latency criterion(C_2) variation

ΔC_2	**Wi-Fi**	**Z-Wave**	**ZigBee**	**Bluetooth**
0%	0,3334	0,2997	0,2375	0,1294
10%	0,3148	0,2977	0,2658	0,1217
20%	0,2962	0,2958	0,2941	0,1139
30%	0,2775	0,2938	0,3225	0,1062
40%	0,2589	0,2918	0,3508	0,0985
50%	0,2403	0,2898	0,3791	0,0908
60%	0,2216	0,2879	0,4074	0,0831
70%	0,2030	0,2859	0,4358	0,0754
80%	0,1844	0,2839	0,4641	0,0676
90%	0,1657	0,2819	0,4924	0,0599
100%	0,14708	0,27995	0,520760	0,05221
0,05322	32,353%	29,865%	25,255%	12,527%

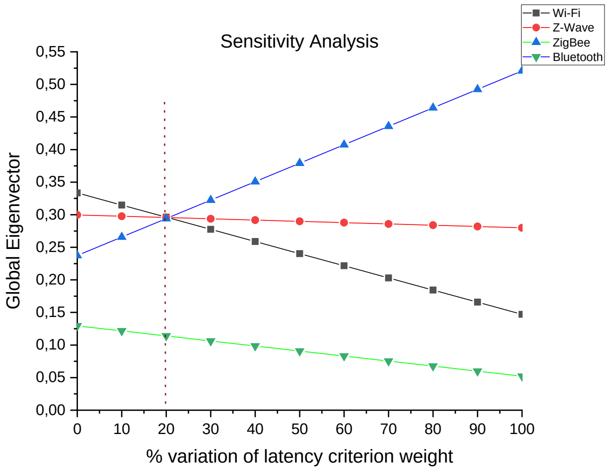


Figure 5.29 – Latency criterion sensitivity

Assuming that the alternatives judgment have had equal weights since they were considered equally secure, Table 5.11 shows the percentage increase in the weight of the security criterion. For example, an increase in weight by 100% would make the alternatives tie, as shown in Figure 5.30.

Table 5.11 – Security criterion(C_3) variation

ΔC_3	**Wi-Fi**	**Z-Wave**	**ZigBee**	**Bluetooth**
0%	0,3283	0,2926	0,2264	0,1526
10%	0,3268	0,2946	0,2350	0,1436
20%	0,3252	0,2966	0,2436	0,1346
30%	0,3236	0,2986	0,2523	0,1256
40%	0,3220	0,3006	0,2609	0,1166
50%	0,3204	0,3026	0,2695	0,1076
60%	0,3188	0,3045	0,2781	0,0985
70%	0,3173	0,3065	0,2867	0,0895
80%	0,3157	0,3085	0,2953	0,0805
90%	0,3141	0,3105	0,3039	0,0715
100%	0,31250	0,31250	0,31250	0,06250
0,30342	32,353%	29,865%	25,255%	12,527%

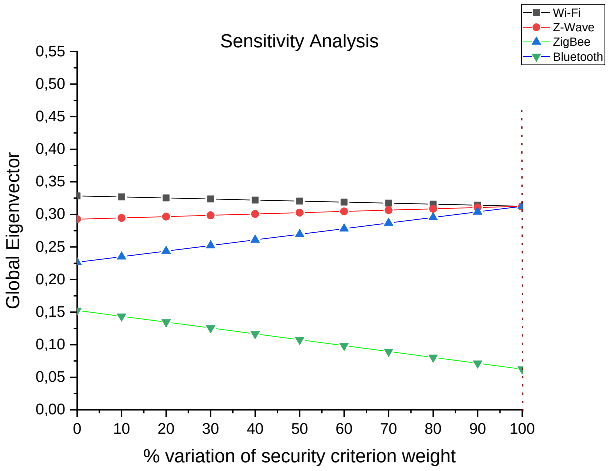


Figure 5.30 – Security criterion sensitivity

Table 5.12 illustrates the trend of the decision vector of the alternatives when the weight of the range criterion is increased. With a 10% increase in the criterion's weight, Wi-Fi technology ties with Z-Wave technology, which tends to gradually lose adherence until finally establishing a tie with ZigBee technology Figure 5.31. However, Wi-Fi alternative remains the winner with a percentage increase in the range weight.

Table 5.12 – Range criterion(C_4) variation

ΔC_4	**Wi-Fi**	**Z-Wave**	**ZigBee**	**Bluetooth**
0%	0,2836	0,3186	0,2631	0,1347
10%	0,3071	0,3068	0,2569	0,1292
20%	0,3307	0,2951	0,2507	0,1236
30%	0,3543	0,2833	0,2444	0,1180
40%	0,3779	0,2715	0,2382	0,1124
50%	0,4015	0,2597	0,2320	0,1068
60%	0,4250	0,2480	0,2258	0,1012
70%	0,4486	0,2362	0,2196	0,0956
80%	0,4722	0,2244	0,2133	0,0900
90%	0,4958	0,2127	0,2071	0,0845
100%	0,51935	0,20089	0,20089	0,07887
0,16955	32,353%	29,865%	25,255%	12,527%

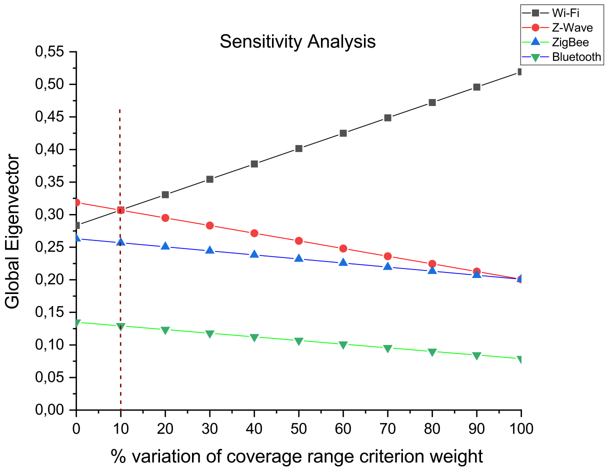


Figure 5.31 – Range criterion sensitivity

Table 5.13, illustrates that when the reliability criterion weight is up to 0.20742, the decision vector shows Wi-Fi as the winning alternative with about 32.353% adherence. However, after a 30% increase in the original value, a break-even point occurs, in which Wi-Fi loses to Z-Wave (31,03%) and ZigBee (30.64%) at above 50% stage increment in the criterion weight. Moreover, because Z-Wave and ZigBee technologies are considered equally reliable, as shown in Table 2.2, they tie at a 100% increment in the weight of the criterion under analysis. Figure 5.32 shows this trend evidencing the sensitivity of the decision when the criterion's weight varies for plus.

Table 5.13 – Reliability criterion(C_5) variation

ΔC_5	**Wi-Fi**	**Z-Wave**	**ZigBee**	**Bluetooth**
0%	0,3665	0,2725	0,2144	0,1466
10%	0,3458	0,2851	0,2328	0,1363
20%	0,3251	0,2977	0,2512	0,1260
30%	0,3044	0,3103	0,2696	0,1157
40%	0,2836	0,3229	0,2880	0,1055
50%	0,2629	0,3355	0,3064	0,0952
60%	0,2422	0,3481	0,3248	0,0849
70%	0,2215	0,3607	0,3432	0,0746
80%	0,2008	0,3733	0,3616	0,0643
90%	0,1801	0,3859	0,3801	0,0540
100%	0,15934	0,39847	0,39847	0,04373
0,20742	32,353%	29,865%	25,255%	12,527%

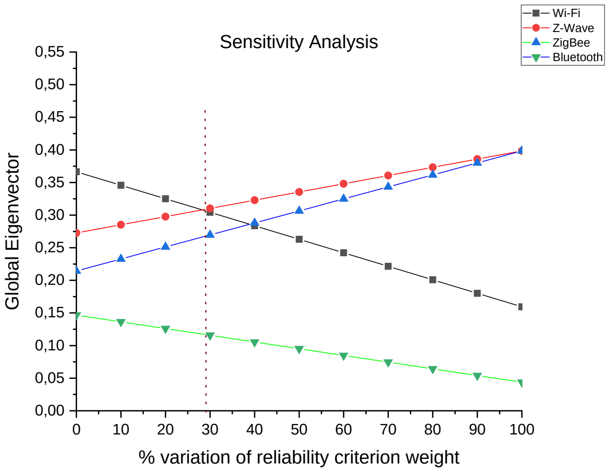


Figure 5.32 – Reliability criterion sensitivity

Table 5.14 shows that the decision vector is not very sensitive to variations in the weight of the interoperability criterion. This is evidenced in Figure 5.33, where even when increasing the criterion's importance in the decision, the Wi-Fi alternative remains the winner, almost constantly, at least until a tie is established at approximately 100% of the weight increase.

Table 5.14 – Interoperability criterion(C_6) variation

ΔC6	Wi-Fi	Z-Wave	ZigBee	Bluetooth
0%	0,3241	0,2924	0,3117	0,0718
10%	0,3238	0,2953	0,2841	0,0968
20%	0,3236	0,2982	0,2565	0,1217
30%	0,3233	0,3011	0,2289	0,1467
40%	0,3230	0,3040	0,2013	0,1716
50%	0,3228	0,3069	0,1737	0,1966
60%	0,3225	0,3098	0,1461	0,2216
70%	0,3222	0,3127	0,1185	0,2465
80%	0,3220	0,3156	0,0909	0,2715
90%	0,3217	0,3185	0,0633	0,2965
100%	0,32143	0,32143	0,035714	0,32143
0,21421	32,353%	29,865%	25,255%	10,527%

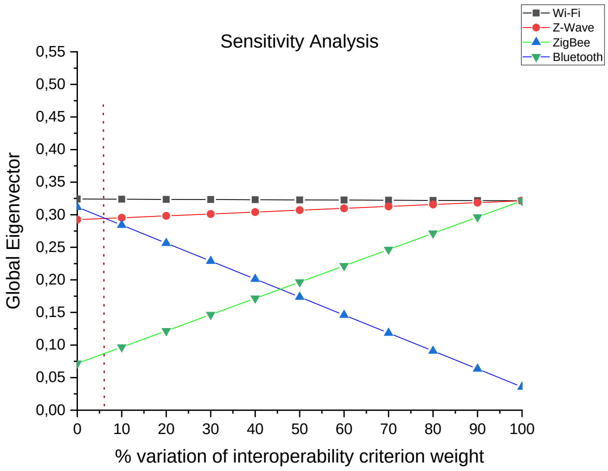


Figure 5.33 – Interoperability criterion sensitivity

By sensitivity analysis, it is possible to conclude that the selection of communication technology for smart grid applications, in general, will depend on the specific requirements of each application. The specific requirements may include the level of mission criticality, the amount of data to be transmitted, the distance between devices, and the need for real-time monitoring and control, as stated in [8, 30]. So, on the one hand, for mission-critical applications, such as distribution and substation automation, security, latency, and reliability will be critically considered. At the same time, the cost may not be a deciding factor. On the other hand, for non-critical applications, such as AMI, in the real-context scenario, the cost may be the deciding factor in selecting communication technology, considering a large number of devices deployments. Nevertheless, cost as a requirement is not part of the scope of this work as a criterion.

5.4 AHP Findings with Respect to the Proposed Case Study

Obviously, as stated before concerning simulation purposes, for the judgment and weights' assignment on the comparison matrices, synthetic values reflecting the Saaty intensity' scale were considered in this case study. However, for the practical application of this methodology, with the use of the Matlab code developed and available in Appendix A, it is essential to ponder the considerations below.

A hierarchical method of picking communication technologies can help decision-makers select the best option at a particular moment. However, adjustments and upgrades will occasionally be required.

The frequency with which adjustments and upgrades may be necessary will be affected by factors such as the pace of change of available technologies, the degree of the organization's dependence on communication technology, and the level of investment the organization is prepared to make in the technology.

Therefore, it is advised to periodically assess the hierarchical structure to ensure it accurately reflects the demands of the company and the market. Despite this, more frequent revisions may be required if there are significant changes in the technologies that are now accessible or the organizational demands.

To prevent biases or tendencies when filling the pairwise comparative matrix, it is recommend that the matrices be made available to different experts and stakeholders with relevant knowledge of the multidisciplinary nature of the adopted criteria. This approach not only improves the process and overall quality of the alternatives but is also just as important as breaking down and prioritizing the criteria.

6 Conclusions and Future Research Directions

This work aimed to select the best communication technology for metering data transfer in home area network applications in a smart grid context. For this purpose, a methodology was presented that can assist stakeholders in the decision-making process.

In Chapter 2, a state-of-the-art is provided regarding electric grid fundamentals and their evolution to smart grids. The basic requirements of a smart grid were also able to be mapped. Additionally, advanced metering infrastructure, topologies, and characterization are addressed in detail. Last but not least, wireless and wired communication technologies, their characteristics, applications, pros, and cons were also discussed.

Notwithstanding, the method chosen for the decision-making analysis was the AHP due to its ease of criteria hierarchization, as grounded in Chapter 3. Therefore, the work sought to deliver better quality decisions, justifying the choice rationally and consistently with data available in the literature review and as presented in Chapter 2.

The case study conducted in this work demonstrated, through an example, how the AHP method can be applied in a real-context scenario using the computational algorithm provided in the Appendix A. It should be noted that the weights assigned to the pairwise comparison matrices for selecting the winning technology were synthetic, as previously mentioned.

Furthermore, among the options investigated, Z-Wave and ZigBee ranked second and third, behind only of Wi-Fi, which proved to be the most adherent technology to satisfy the specified requirements.

Hence, Wi-Fi scored 32.35%, making it the preferred technology due to its high data transfer rates, widespread availability, coverage distance, and compatibility with a wide range of devices.

Furthermore, Z-Wave scored 29.86% and was adherent due to its reliability, security, and compatibility with smart home devices. ZigBee, by other side, scored 25.26%, due to it‘s suitability for low latency requirements, although it has limited coverage and slower data transfer rates.

In addition, Bluetooth scored the last score of 12.53%, and while it is commonly used, it had limited coverage and higher latency.

So, the analysis suggests that Wi-Fi and Z-Wave are preferred for wireless communication, but the choice of technology depends on specific requirements. And last and not least, the sensitivity analysis demonstrated the impact that each criterion can have on the creation of the decision vector.

However, suppose this method is to be used in a real-context scenario. In that case, it is recommended to involve subject matter experts and gather input from stakeholders to ensure that the weights assigned to the evaluation are not only as unbiased as possible but also reflect the specific goals and objectives of the project. This will help to ensure that the final judgment is as accurate as possible.

6.1 Future Research Directions

The results of this research can contribute to other research and further investigations, such as:

To Repeat this research by choosing more criteria such as scalability, bandwidth, etc. Since for smart grids to have higher performances, there are many requirements, and just some of them were considered in this work. Therefore, further studies can examine other criteria to have a complete point of view on the subject.

Future research could also explore selecting the best technologies for NAN and WAN to align with the global trend on sustainable energy matrix and integration of communication technologies.

Furthermore, this work focused on the most consolidated technologies in the market, such as Wi-Fi, Z-Wave, etc.; however, in recent years, new technologies have been emerging, such as the IoT, for example, which was not addressed in this work. Therefore, in future work, similar studies may explore new potential technologies.

It would also be utmost to explore alternative decision-making methods available in the literature, such as the ANP (Analytic Network Process), AI (Artificial Intelligence), or a combination of both, to improve decision-making models' accuracy potentially.

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Appendix

APPENDIX A – MATLAB Code

```matlab
for comments_instructions =[]
   To use this code, all you need to do is:
   In matlab, create a 'file.m' then copy and past the code in,and its OK.
   Just follow the code requests to run it, and watch the magic happen
   You can customise the labels in the means that fits your interests.
end
clc;
clear;
close all;


%% CRITERIA COMPARISONS
    cr_or = input('Inform the square nxn Criteria Matrix order:\n');
    fprintf('Criteria matrix judgement with respect to the goal\n');
    cr_Mat = input_matrix(cr_or);
    fprintf("Matrix :\n");
    disp(cr_Mat);

    fprintf('Criteria normalized matrix with respect to the goal\n');
    cr_Norm = calc_norm(cr_Mat);
    [r,c] = size(cr_Norm);
    disp('Criteria comparison eigenvector:');

    cr_title = "Criteria decision vector with respect to the goal";
    cr_bType = "barh";
    labels_cr = {'C1', 'C2', 'C3', 'C4', 'C5', 'C6'};

```

```
    [CI, CR, lambda_max] = ahp_consistency_index(cr_Mat, cr_Norm, r, labels_cr, cr_title, cr_bType);
    sprintf('%c max = %.4f\nCI = %.4f\nCR = %.4f', char(955), lambda_max, CI, CR)

%% ALTERNATIVIES COMPARISONS
    i=1;
    local_priority = {1,length(cr_Norm(:,1))};
while i <= length(cr_Norm(:,1))

    or = input('Inform the Alternatives square nxn Matrix order:\n');
    sprintf('Alternative matrix judgement with respect to the criterion (%d): ',i);
    alt_Mat = input_matrix(or);

    fprintf("Matrix M:\n");
    disp(alt_Mat);

    fprintf('Alternative normalized matrix with respect to the criterion: %.0f\n', i);
    alt_Norm = calc_norm(alt_Mat);

    alt_bType = 'barhl';
    alt_title = sprintf('Alternative decision vector with respect to the C%.0f\n',i);
    labels_alt = {'A1', 'A2', 'A3', 'A4'};%You can edit according to your interest

    [CI, CR, lambda_max] = ahp_consistency_index(alt_Mat, alt_Norm, or, labels_alt, alt_title, alt_bType);

    sprintf('%c max = %.4f\nCI = %.4f\nCR = %.4f', char(955), lambda_max, CI, CR)

    local_priority{i}= matrix_eigenvector(alt_Norm);
    i = i+1;
end
%% GLOBAL RANKING
```

```
    decision_Matrix = cell2mat(local_priority);

    priority_score_correlation = ahp_global_priority(decision_Matrix, matrix_eigenvector(cr_Norm));

    disp('Global scores rankig:');
    fprintf('%.4f\n', priority_score_correlation)

    rank_title = "Global scores"; %You can edit according to your interest
    rank_bType = "bar";

    labels_rank = {'A1', 'A2', 'A3', 'A4'}; %You can edit according to your interest

    ahp_ranking_of_priority(priority_score_correlation,labels_rank,rank_title,rank_bType);

%% FUNCTIONS
%1- Create input Matrix
function M = input_matrix(n)
    M = eye(n); % Creates an nxn matrix with diagonal set to 1
    for i = 1:n
        for j = i+1:n %Fills the upper triangle of the comparison matrix
            try
                value = input(sprintf('Enter the weight for the comparison (%d,%d): ', i, j));
                while isempty(value) || ~isnumeric(value) % Verify if is a numeric value or empty
                      value = input(sprintf('Invalid value. Enter the weight for the comparison (%d,%d): ', i, j));
                end
            catch
                value = input(sprintf('Enter the weight for the comparison (%d,%d): ', i, j));
            end
```

```
            % catch the reciprocal values from the upper triangle and fill lower
            % triangle of the comparison matrix
            M(i,j) = value;
            M(j,i) = 1/value;
        end
    end
end



%% 2- Calculate the normalized Matrix
function [normvect] = calc_norm(M)

    sM = sum(M);
    normvect = M./sM; %Here it calculate the normalization

    disp('Matrix Normalization');
    disp(normvect);
end

%% 3- Sum each row for eigenvector calculation
function [eigenvector] = matrix_eigenvector(M)
    [r, c] = size(M);
    for i = 1: r
        sumRow = 0;
    for j = 1:c
        sumRow = sumRow + M(i,j);
    end
        v(i) = (sumRow);
    end
    eigenvector = transpose(v)/r; %This tronspose the eigenvector
end

%% 4- Saaty Intensity scale
function ri = rand_index(n)
    saatyScale = [0.00 0.00 0.58 0.90 1.12 1.24 1.32 1.41 1.45 1.49 1.51 1.48 1.56 1.57 1.59];
```

```
    ri = saatyScale(n);
end

%% 5- Consistency calculations, CI, Lambda_max and CR
function [CI, CR, lambda_max] = ahp_consistency_index(M, matrix_Norm,r,labels, title, barType)
    % Call and get the eigenvector of the consistency matrix function
    eigenvector = matrix_eigenvector(matrix_Norm);

    % Display the eigenvector
    disp(eigenvector);

    % Get the eigenvalues of the consistency matrix
    eigenvalues = (M*matrix_eigenvector(matrix_Norm))./matrix_eigenvector(matrix_Norm);

    % Get the lambda max
    lambda_max = mean(eigenvalues);

    % Calculate the consistency index (CI)
    CI = (lambda_max - r)/(r-1);

    % Calculate the consistency ratio (CR)
    CR = CI/rand_index(r);

     % Call and get the ploting function
    ahp_ranking_of_priority(eigenvector, labels, title, barType,lambda_max,CI,CR);

    % Call the Checking the consistency of the matrix function
    check_consistency(CR);
end

%% 6- Check if the matrix is consistent or not
function check_consistency(cr)
    if cr > 0.1
```

```
        disp('Matrix judgment is not consistent, please adjust your judgments')
    else
        disp('Matrix judgment is consistent')
    end
end

%% 7 - Calculate the decision vector
function global_priority = ahp_global_priority(alt_priority, cr_weight)
       %Calculate the comparisons global scores
    global_priority = transpose(sum(transpose(alt_priority).*cr_weight));
end

%% 8- This function plots the judgment rankings
function plot_priority = ahp_ranking_of_priority(rank, labels,...
    title, barType,lambda_max,CI,CR)
    % rank is the decision vector
    % labels is the array of element labels
    figure()
    switch barType
        case 'barh' %For criteria plotations
            plot_priority = barh(rank*100);
            xlabel("WEIGHTS [%]");
            text(0.7638,0.8811,0,sprintf('%c max = %.4f\nCI = %.4f\nCR = %.4f',...
                char(955), lambda_max, CI, CR),'Units','normalized',...
                'HorizontalAlignment','left','VerticalAlignment','middle');
            ylabel('CRITERIA');
            ay = gca;
            ay.YTickLabel = labels;

        case 'barhl' %For alternatives plotations
            plot_priority = barh(rank*100);
            xlabel('WEIGHTS [%]');
```

```
            text(0.7638,0.8811,0,sprintf('%c max = %.4f\nCI = %.4f\nCR = %.4f',...
                char(955), lambda_max, CI, CR),'Units','normalized',...
                'HorizontalAlignment','left','VerticalAlignment','middle');
            ylabel('ALTERNATIVES');
            ay = gca;
            ay.YTickLabel = labels;

        case 'bar' %For global scores plotations
            plot_priority = bar(rank*100);
             xlabel('ALTERNATIVES');
             ylabel('WEIGHTS [%]');
             ax = gca;
             ax.XTickLabel = labels;
    end
    grid on;
    suptitle(title);
end
```