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Network Planning of a Home Hospitalization Service Integrating Telemonitoring Solutions

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AI Declaration

During the preparation of this master's thesis, the author utilized ChatGPT for the following purpose:

1. ChatGPT was used to support the code development in Python and to refine language for improved clarity.

2. After using ChatGPT, the author diligently reviewed and edited the content produced by the tool. We take full responsibility for the final content presented in this thesis.

By signing this declaration, we affirm that the content of this master's thesis reflects our original work, augmented by the responsible use of AI.

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To my family, I offer my heartfelt thank you for their unconditional support and belief in me and my potential. Even from far away, I never felt alone. To Diogo, a special thank you for his unwavering support and companionship throughout this journey.

The end of a chapter, one defined by hard work and personal growth. Five years, two universities in two different countries, and one feeling that remains: gratitude. Gratitude for the challenges that shaped me, for the professors, colleagues, and friends who made this journey worthwhile, and for the opportunities that allowed me to grow.

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1 Introduction

Healthcare systems worldwide are under increasing pressure due to population ageing, rising healthcare needs and expenditures, and persistent shortages of hospital beds and healthcare professionals. In Portugal, these challenges are also observed. The National Health Service (SNS) faces underfunding, workforce shortages, and regional inequalities, which have been exacerbated by the sovereign debt crisis and the COVID-19 pandemic. In response to these pressures, Home Hospitalization (HH) has emerged as an alternative model of care that delivers hospital-level treatment at home and has demonstrated benefits such as improved patient satisfaction, reduced costs, and increased bed capacity. In Portugal, although the model has been expanding since its introduction in 2015, its broader implementation remains constrained by operational challenges, limited digital integration, and concerns about its scalability beyond dense urban areas.

One way to address these constraints is through the integration of telemonitoring technologies into the HH services, which allow for the remote and continuous monitoring of patients' health. Although the use of telemonitoring in Portugal is still at an early stage, it has shown potential to improve access, increase infrastructure efficiency and strengthen patient–physician interactions. International examples have shown that these technologies can support more efficient and resilient care delivery. In this way, this thesis is motivated by the need to understand how telemonitoring can contribute to the scalability of HH services within the Portuguese context.

To this end, it combines a conceptual analysis—based on the WHO's digital health intervention framework—with a multi-objective optimization model. The model supports decision-making on network configuration and capacity planning by simultaneously considering cost and service capacity, while also accounting for geographic coverage. It considers operational constraints such as the availability of medical staff, proximity between units and patients, and the feasibility of patient allocation.

During the development of the study, certain difficulties were encountered, particularly related to limited data availability and the absence of detailed demand forecasts for HH services. Nevertheless, the model still provided a structured and adaptable approach to support the planning of telemonitoring-enabled HH services.

2 Home Hospitalization

2.1 Definition

Worldwide, healthcare systems are struggling with ageing population, increasing healthcare needs and expenditures, and shortages of hospital beds and health professionals, often leading to treatment delays, higher mortality risk, decreased satisfaction for patients and staff and increased costs for patients and healthcare systems (Leong et al., 2021). These factors pose a threat to the sustainability and quality of care and emphasize the urgency to explore innovative solutions (Leong et al., 2021).

In this way, Home Hospitalization (HH), also known as Hospital-at-Home (HaH), appears as an alternative model of care where professionals deliver hospital-level care at home for conditions typically requiring hospitalization (Caplan et al., 2012). It serves a dual purpose by providing an alternative to in-hospital care while also offering an alternative option for managing medical conditions without the unnecessary added risk of hospital acquired infections (Knight & Lasserson, 2021). It is very useful during seasonal outbreaks which often place a significant strain on acute-care services (Knight & Lasserson, 2021).

This healthcare model includes two main models: Early Supported Discharge (ESD) and Admission Avoidance (AA). ESD accelerates the discharge of admitted hospital patients, replacing part of the hospital care with home care, whilst AA focuses on preventing hospital admissions altogether by admitting patients directly into HH (Leong et al., 2021), thereby helping to release hospital bed capacity in comparison to conventional hospitalization.

2.2 Benefits and Challenges

Home Hospitalization offers several benefits over traditional inpatient care. According to Chua et al., 2021, these advantages include a more patient-centered approach, improved clinical outcomes, enhanced care continuity during and after HH, and increased hospital bed capacity.

Additionally, research supports that patients tend to experience greater satisfaction with HH compared to hospital stays due to the personal nature of care and the therapeutic value of remaining at home (Wilson et al., 2002). Related with the previously mentioned improved clinical outcomes, studies also demonstrate that HH reduces mortality and readmission rates (Caplan et al., 2012). Furthermore, it has proven to reduce costs in a statistically and clinically significant way across all age groups (Caplan et al., 2012), with many trials and observational studies highlighting its cost-efficiency, frequently reporting favorable financial outcomes when compared to traditional hospitalization (Knight & Lasserson, 2021).

Despite the documented benefits of the HH model, several limitations were also identified. Although several HH models have been studied there is still controversy surrounding the overall effectiveness of this approach, partly due to the heterogeneity among the various models (Leff, 2005).

One of the main challenges is the lack of 24-hour patient supervision compared to hospital care, which can lead to feelings of vulnerability, particularly at night (Chua et al., 2021). The model also places a significant burden on family caregivers, who play a significant role in multi-task interventions, characterized by the intensity and frequency of the care which often implies their active involvement (Rossinot et al., 2019).

From an operational perspective, these models often suffer from underdeveloped and unclear workflows, with health professionals encountering difficulties in understanding the entry and exit points for HH and in identifying their roles within the models. Furthermore, there are also challenges in the screening and recruiting process of suitable patients with healthcare professionals considering it tedious and time-consuming (Chua et al., 2021).

Technologically, HH programs face several limitations, many of which arise from lack of integration of technology into existing workflows, leading to issues such as electronic health records not syncing in real time. In addition, although only documented by a few studies, some of these models that have introduced remote monitoring systems and teleconsultations have reportedly disrupted patients' daily lives and presented technical issues (Chua et al., 2021).

All in all, the widespread adoption of Home Hospitalization has the potential to increase the resilience of the acute-care system, enabling it to accommodate increasing demand without increasing the number of physical hospital beds. However, achieving this will require a fundamental reassessment of what constitutes Hospital-level care (Knight & Lasserson, 2021).

Furthermore, the future success of the HH model will require investment in diagnostic infrastructure, the development of innovative training pathways, and a broad cultural adaptation to risk, while fostering stronger collaboration with the patients it serves. This model aims not only to provide an operational solution to an acute-care system on the verge of saturation but also to take a step towards better, more personalized care (Knight & Lasserson, 2021). Strong communication among healthcare professionals, patients and their family members along with effective collaboration between professionals are the building blocks for improving access to care in the community setting, and better integration of technological advancement can greatly support this effort (Chua et al., 2021).

2.3 The Effect of the Covid-19 Pandemic

While HH is not a new concept, given that it was first introduced in the 1940s in the United States of America as a potential solution to the shortage of hospital beds (Azevedo, 2020), the COVID-19 pandemic has highlighted its importance (Chua et al., 2021). This period served as a catalyst for transforming healthcare delivery at home, accelerating the implementation of innovative approaches to slow the spread of the virus. However, it also highlighted the existing challenges in the home care sector at the time, exposing its lack of recognition by public authorities and many health professionals (Brocard et al., 2021).

Despite this, HH emerged as a critical solution for patients with chronic diseases and mild cases of COVID-19 to alleviate the strain on hospitals, allowing patients to be cared for and monitored at home (Brocard et al., 2021). Additionally, the pandemic also created an opportunity to rethink care at home (Bestsennyy et al., 2022).

Indeed, virtual care grew significantly, with telehealth becoming a widely used option that many consumers planned to use in the post-pandemic period. Plus, there has also been increased demand for post-acute and long-term care**,** as more patients consider home care over traditional facilities (Bestsennyy et al., 2022).

Ultimately, the adoption of technologies like remote monitoring accelerated during this period, proving its importance as a support to home care models. New technologies have expanded the ability to monitor patients remotely, track progress and receive alerts when issues arise (Bestsennyy et al., 2022).

3 Portugal's Health System

3.1 Overview

The National Health Service (*Serviço Nacional de Saúde* – SNS) in Portugal is a universal healthcare system, mainly funded through taxes, covering all residents. Primary and hospital care are provided by a combination of public and private providers, with family doctors serving as access regulators to specialized and secondary care (OECD, 2023).

The Ministry of Health is responsible for overseeing activities related to planning, monitoring, guidance, and regulation in the SNS. Locally, there are five regional health administrations responsible for SNS hospitals, the management of the health centers and public providers of primary healthcare, as well as the implementation of national health policies (OECD, 2023).

In addition to the National Health Service, healthcare coverage is also provided through two other channels, which mainly serve as supplementary options. The first includes various health subsystems (public and private) which are insurance schemes covering specific professional groups such as public employees, military personnel, and workers in other sectors. The second one consists of voluntary private health insurances schemes that offer access to additional benefits (OECD, 2023).

3.2 Health Trends in Portugal

Following the trend of other EU countries, Portugal has experienced significant population ageing over the past two decades, with those aged 65+ years old accounting for 23.7 % of the population, and life expectancy reaching 81.7 years in 2022 (OECD, 2023). Cardiovascular diseases and cancer are the leading causes of death in Portugal (OECD, 2023). According to EU-27 data for 2022, Portugal had the third highest proportion of people with chronic illness or long-term health issues, with 44.77% of the population affected (INE, 2024).

Portugal's population is also characterized by low levels of mental well-being and high prevalence of patients with multimorbidity [1](Miranda et al., 2023). Multimorbidity is associated with a higher number of hospitalizations, nosocomial complications, institutionalizations, polypharmacy, adverse drug reactions, as well as losses in functional capacity and quality of life, and increases in mortality and the rate of use of medical resources, resulting in a significant rise in healthcare costs (Azevedo, 2021).

3.3 Health System Current State and Challenges

Portugal has made significant progress in improving healthcare coverage and its quality. Nevertheless, due to two severe economic and social crisis – the sovereign debt crisis and the COVID-19 pandemic – the SNS has been affected, aggravating access inequalities and leading to the exhaustion and demotivation of health professionals (Miranda et al., 2023).

Like many other western countries, Portugal also suffers from underfunding and scarcity of human resources (Miranda et al., 2023). The World Health Organization (WHO) has specifically highlighted the scarcity of human resources as a major challenge for Portugal's health sector (Rádio Renascença, 2022), a situation that was pushed to its limits during the pandemic (Miranda et al., 2023).

The SNS faces ongoing difficulties also in retaining both family doctors and nurses, primarily due to low wages and exhausting working conditions, which reduce the appeal of public sector roles. Portugal has fewer nurses than most other EU countries, a situation partly attributed to relatively low nursing graduates and the burnout experienced by the nursing staff. Furthermore, the distribution of healthcare professionals is unequal, with 70% of healthcare

[1] Presence of multiple chronic diseases in the same individual.

workers concentrated in the Lisbon and Northern regions, despite these regions representing only 62% of the total population (OECD, 2023).

Although the government has taken steps to improve nurse retention, efforts to address the shortage of family doctors have been insufficient. The scale of accessibility challenges varies across different services and regions, with Portugal's southern areas often experiencing more severe difficulties (OECD, 2023).

Also relevant, the relatively low density of hospital beds - 3.5 beds per 1,000 habitants in 2021- makes Portugal rank below most EU countries. In addition, there are relevant disparities in the availability of beds across different regions, with the highest densities found in the major metropolitan areas (OECD, 2023).

The WHO also emphasized the need for investment in processes, technologies that accelerate service delivery, and improvements in the training and capacity-building of healthcare professionals (Rádio Renascença, 2022). In the long term the situation of SNS will become unsustainable due to the saturation of healthcare services, making it urgent to reform the provision of hospital-level care, in which Home Hospitalization emerges as a safe and effective alternative (Azevedo, 2021).

3.4 Home Hospitalization in Portugal

Home Hospitalization in Portugal began at Garcia de Orta Hospital in 2015, pioneering the creation and implementation of the country's first HH program, inspired by the experience of the Infanta Leonor University Hospital in Madrid (Delerue, 2021). From then until now, the model has continued to evolve and expand, with most hospitalized conditions in the HH units mirroring those seen in traditional hospitalization departments, including respiratory, urinary, skin and soft tissue infections, heart failure, and post-operative wound or prosthesis infections (Azevedo, 2020).

At the end of 2022, a total of 25,280 patients had been treated under the HH program, and by October 2023, around 340 patients were being hospitalized at home, equating to the capacity of a medium-sized hospital (Delerue, 2023). Notably, the program not only surpassed the target set for 2024, which aimed to treat 5,000 patients at home by 2024 but, in fact almost doubled it, with 9,000 patients being treated by 2022. Looking ahead, there is the plan to triple the program's capacity by 2026, reaching the capacity of approximately 1,000 beds (SNS, 2023).

In Portugal, as in many countries, the COVID-19 pandemic contributed to the growth of home hospitalization services (Gaspar, 2020). During it the SNS had to be rapidly restructured to manage the surge in demand for care, mostly from patients with respiratory illnesses.

Based on WHO recommendation, the Home Hospitalization Study Group of the Portuguese Society of Internal Medicine developed a document on the role that HH Units could play which gave place to the publishing of a guideline outlining the terms under which it could be implemented (Delerue, 2021). Indeed, this decision paved the way for demonstrating the undeniable impact of Home Hospitalization, which also showed in Portugal most of the advantages previously discussed and felt worldwide throughout the pandemic (Delerue, 2021).

Following the pandemic, there is growing pressure in Portugal to adopt new practices that promote more efficient, sustainable, and equitable healthcare. Although HH has shown promising outcomes it is not without challenges, as it was mentioned in Chapter 2.2. Furthermore, doubts remain about its scalability. Indeed, critics argue it is only viable in dense urban areas with dedicated teams and is limited by the small pool of eligible patients and the complexity of coordinating multidisciplinary care. Nonetheless, emerging evidence suggests these barriers can be addressed through telehealth integration and redesigned care delivery models (Truong & Siu, 2025).

In fact, telemonitoring can be a valuable solution to address some of the key challenges identified both within the Portuguese's health system context and in the HH service. More specifically, it can improve access, increase infrastructure efficiency and strengthen patient-physician relationships (Miranda et al., 2023). Additionally, telemonitoring has also proven to enhance the capacity of the healthcare system, empower patients and foster great treatment commitment (Azevedo et al., 2021).

4 Problem Definition

The Portuguese healthcare system is under tension due to an aging population, a shortage of healthcare professionals and increasing demand for hospital services. While HH represents a promising alternative by delivering hospital-level care in patients' homes, it present challenges and its large-scale implementation remains limited by the lack of digital integration.

Telemonitoring, a tool which is still underdeveloped in Portugal, has proven to contribute to addressing these challenges and alleviating the burden on healthcare staff, as will be further explored in the literature review. In this way, the goal of this dissertation is to develop a model that can help evaluate the impact of a telemonitoring solution on the scalability of Home Hospitalization services, while also accounting for its associated costs.

5 Literature Review

5.1 Telemonitoring: A Solution

It is known that the landscape of healthcare delivery has seen transformative changes in recent years with advances in technology playing a crucial role in shaping its future. As technology continues to evolve and health systems with it, the integration of telemedicine is set to play a vital role in the future of healthcare delivery (Vudathaneni et al., 2024).

Telemedicine is a broad term that encompasses any medical activity involving an element of distance which, in recent years, has evolved, giving way to more popular terms like "telehealth", "online health", and "e-health" (Wootton, 2001). Initially used in one of its first official applications to monitor astronauts during space missions, telemedicine is now widely applied to everyday patient care and has experienced exponential growth due to the COVID-19 pandemic (Serrano et al., 2023).

Remote patient monitoring (RPM), also known as telemonitoring (Serrano et al., 2023) or remote patient monitoring system (RPMS) (Boikanyo et al., 2023), is one of the strategies of telemedicine (Serrano et al., 2023). It offers a way for healthcare practitioners to gather real-time information on the physiological conditions of patients and remotely evaluate their health status, enabling them to observe patients' parameters and intervene if abnormalities arise (Serrano et al., 2023).

In a RPMS, physiological data - such as heart rate, respiratory rate, body temperature and blood oxygen saturation and pressure - is collected through biomedical sensors. Additionally, patients can also report symptoms and other health-related information directly through digital platforms, known as Patient Reported Outcomes (Knapp et al., 2021). This moves traditional clinical care into patients' homes with the data being wirelessly transmitted to healthcare providers to facilitate timely and informed decisions (Boikanyo et al., 2023).

RPM technologies for acute care can be classified by device modality used to collect biometric data and include ambient, wearable (Whitehead & Conley, 2022) – one of the most used, both consumer and medical grade, that can monitor and record information on physiological conditions and activities (Serrano et al., 2023) - or intermittent devices (Whitehead & Conley, 2022). Furthermore, more invasive technologies include devices such as pacemakers and implantable cardioverter-defibrillators, that are paired with a platform to gather patient data (Serrano et al., 2023).

These systems target specific groups of patients such as those with chronic diseases, infectious diseases during isolation, and those with limited mobility or other disabilities.

Additionally, they are also used for post-surgery patients, newborns, and elderly patients (Boikanyo et al., 2023).

5.1.1 Benefits and Challenges

Overall, telemonitoring emerges as a critical component, offering unprecedented opportunities to improve accessibility, improve patient outcomes, and optimize healthcare resource utilization (Vudathaneni et al., 2024).

Regarding its application benefits, in general, healthcare practitioners believe that RPM is feasible for application with an additional consensus that telemonitoring strategies will become increasingly relevant. RPM allows a continuous monitoring of patients' conditions between clinic visits, which enables early identification of deterioration and timely intervention. This is particularly beneficial for chronic patients, as it allows for better outcomes. Additionally, RPM can decrease unnecessary clinic visits when patients are recovering well, and when visits are needed, practitioners can work more efficient due to the supplied data (Serrano et al., 2023).

Another significant benefit of telemonitoring is the ability to provide a more realistic assessment of certain vitals, such as blood pressure, which might be inaccurately evaluated during clinic visits due to the "white coat syndrome"[2]. By allowing the collection and long-term storage of data, RPM enables an overview of patients' health status and allows clinicians to identify health trends, supporting the creation of more personalized care plans tailored to the patient needs (Serrano et al., 2023).

Furthermore, RPM plays an important role in patient empowerment by increasing patient awareness of their health and condition, fostering greater confidence in self-management which ultimately helps them maintain a higher quality of life (Serrano et al., 2023).

RPM has shown promise in aiding safe and efficient remote care for chronic conditions. However, its use within the HH model remains limited, despite significant opportunities to increase patient eligibility, improve safety, and reduce costs (Whitehead & Conley, 2022).

Indeed, the robust and efficient collection of more frequent vital signs via RPM could expand patient eligibility for HH and even create a digital health safety net that enables high quality of care. This expansion in eligibility could enable HH programs, which have traditionally operated under capacity, to care for a larger census and decrease allocated fixed costs per hospitalization (Whitehead & Conley, 2022). Additionally, as supported by most of

[2] Phenomenon where a patient's blood pressure is elevated when measured in clinical settings due to anxiety or stress caused by being in a medical environment.

the existent studies (Michaud et al., 2018), RPM has the potential to assist HH models to achieve economies of scale and decrease direct variable costs (Whitehead & Conley, 2022), although the costs of these programs vary according to program component, disease type, equipment used, and services provided (Michaud et al., 2018). Note, however, that implementing a technology-based solution like telemonitoring involves substantial costs during the initial setup phase, which requires significant investment to establish access to infrastructure. In addition, there are also costs with ongoing patient care which requires the involvement of healthcare, administrative and social work professionals and with continuous transmission and management of data (Miranda et al., 2023).

Telemonitoring systems like RPM, are increasingly needed in healthcare due to their characteristics that support continuous monitoring, diagnosis and treatment (El-Rashidy et al., 2021). Nevertheless, there are still challenges associated that must be considered.

Serrano et al. (2023) identified several concerns from healthcare practitioners. These included a focus on the increased workload resulting from the large amount of patient data, additional issues highlighted by the possibility of an increase of patient anxiety due to constant disease reminders, data inaccuracy and limited trust of technology, privacy and security vulnerabilities, and the lack of consensus on financial responsibilities. Additionally, they also state a preoccupation related to one of the main groups targeted by remote monitoring – elderly patients – which can find these technological solutions disorienting.

Existing literature indicates that telemonitoring is still in its infancy in comparison to its true potential to advance the HH model of care. Further research and experience that inform operational and technical as well as policy considerations are needed (Whitehead & Conley, 2022).

While numerous review studies have demonstrated the effectiveness of telemedicine in facilitating home-based disease control and management compared to traditional care models, few have assessed the associated program costs. Although the existing studies all indicate cost reductions, often cost structures were either incomplete or not presented in detail. This lack of information hinders home-based telemedicine programs to make a solid economic case to the main stakeholders when considering reimbursement or investment in these programs (Michaud et al., 2018). Additionally, scalability assessment, meaning ensuring population-wide access to the benefits of this technology, is also critical but scalability studies are scarce (Azevedo et al., 2021). Nevertheless, successful examples of its application begin to show results.

5.1.2 The concept of Virtual Wards

Telemonitoring has been successfully applied in several contexts. In the case of HH, the concept of Virtual Wards, also known as remote home monitoring models (Vindrola-Padros et al., 2021), emerged as a product of introducing telemonitoring in HH services. This model is a hospital-led, technology-enabled alternative to inpatient care that allows patients to receive acute care, monitoring, and treatment at home by combining remote monitoring, through apps, wearables or other devices, with face-to-face interventions (Norman et al., 2023).

The concept gained prominence when England's National Health System – pioneer and current leader in the implementation of these models - made it a central component of its flagship policies in 2022, aiming to reduce high hospital occupancy rates and streamline the discharge process into community-based care. By the end of 2023, more than 240 000 patients had already been treated on virtual wards, many who avoided hospitalization altogether (Jess Hacker, 2024).

Moreover, NHS England established the goal to deliver 24 000 virtual ward "beds", equivalent to the ratio of 40 to 50 available beds per 100 000 residents, by the end of 2023 (NHS England, 2023a). As of late 2024, Integrated Care Systems continues to expand their virtual ward offerings, indicating promising progress towards meeting this target and further expansion is expected as virtual wards become increasingly integral to the broader health and social care landscape (Sheasby, 2025).

Remote home monitoring models have been adopted also in the US, Australia, Canada, the Netherlands, Ireland and China with variations in some criteria such as monitoring frequency or modalities (different combinations of telephone or video calls and use of applications or online portals; Vindrola-Padros et al., 2021).

5.2 Telemonitoring in Portugal

In Portugal, telemonitoring has been rapidly growing, particularly during the pandemic, driven by the telehealth governance model and public reimbursement mechanisms (Miranda et al., 2023). Telemonitoring has come to ensure the consolidation and evolution of the HH model towards an even more ambitious level (Campos Fernandes, 2025). But, despite all progress, the country is still in the early stages of telemonitoring adoption, and the number of monitored patients remains low.

Nonetheless, some clinical studies have been conducted in Portugal on heart failure, sleep apnea, chronic obstructive pulmonary disease and asthma, evaluating the program impacts mainly on clinical outcomes. Results have shown reductions in emergency department and hospital admissions, lower condition-related and all-cause mortality, enhanced patient quality of life and perception of supports, as well as reduced healthcare costs when in comparison to usual care (Miranda et al., 2023).

The National Health System of Portugal itself has taken steps towards this digitalization of health by providing an app – Telemonit SNS 24 – based on a telemonitoring platform that enables healthcare professionals to carry out remote, proactive and personalized interventions using the data received and displayed in their professional interface (SNS, 2025b). The app aims to support the management of patients' health, in particular (but not only) those with chronic conditions, by providing continuous monitoring and assistance to users.

Other examples of progress include Santa Marta Hospital that has integrated technology to remotely assess cardiac patients, improving proximity and continuity of care without physical presence (Florentino, 2020). Further recognition came with Hospital Garcia de Orta, the pioneer in home hospitalization in Portugal, with the implementation of a home hospitalization model supported by remote monitoring technology (SNS, 2021).

However, the country still faces some challenges in the adoption of these programs. These obstacles include the need for more training and organisational support to allow the effective adoption of digital capabilities, thereby reducing the burden of adoption and integration of these technology-enabled solutions within existent care pathways. Other major areas of concern in the process of fostering telemonitoring adoption include low digital literacy among patients and governance. Furthermore, more knowledge on telemonitoring implementation, adoption and dissemination is still needed to inform decision-makers on how to scale up and establish remote interventions as a standard practice in chronic, recovery or continued care settings (Miranda et al., 2023).

Future research is still needed to understand how to integrate the technology into current care pathways, with a focus on analysing and promoting its integration in existing workflows, developing new care delivery and business models. In addition, creating tools to plan, monitor and evaluate the benefits, risks, and costs of these initiatives, as well as investigating new settings where telemonitoring can foster improved access and quality of care are needed (Miranda et al., 2023). As telemonitoring continues to evolve becoming an important part of healthcare systems, it is increasingly important to explore capacity planning models that can support the scalability, resource allocation and operational efficiency of these technology-enabled pathways.

5.3 Network Design and Capacity Planning

Network design and capacity planning models have evolved alongside healthcare systems as these have become more complex and as the need for more efficient, patient-centered care delivery has grown. In healthcare, these planning processes are particularly critical as they require managing scarce and specialized resources under conditions of uncertainty and public scrutiny. Failures in such planning can have serious consequences, including delays, inefficiency, financial losses, and adverse impacts on patient outcomes (Sharifi & Saberi, 2014).

In traditional healthcare settings, early efforts to plan capacity often relied on discrete-event simulation models. While simulation remains valuable for descriptive analysis, these models can be data-intensive, time-consuming to validate, and limited in prescribing efficient solutions. Consequently, optimization-based methods have emerged as more systematic approaches to guide strategic decisions (Li et al., 2016).

Building on this evolution, mathematical programming has been widely applied in healthcare planning, particularly through location-allocation models that combine questions of where to locate services with how to allocate demand. For example, Mestre et al. (2015) developed stochastic location-allocation models to reorganize hospital networks under uncertainty, demonstrating how such approaches can balance cost efficiency and equitable access. More recently, Grange et al. (2024) proposed a mixed-integer programming model to optimize the location and staffing of virtual ward hubs across Wales, integrating workforce requirements, equipment needs, and demand variability within a scenario-based framework.

Despite these contributions, much of the literature has focused predominantly on single-objective formulations, typically prioritizing cost minimization over broader considerations such as access and equity (Cardoso-Grilo et al., 2021). There is growing recognition that planning models should integrate multiple objectives. For instance, functions aggregating competing goals into a single objective or constraint-based methods can support decision-making that reflects the trade-offs inherent in health system design (Cardoso et al., 2015).

In the context of home healthcare, planning decisions can be classified across three broad levels: strategic, tactical, and operational (Chabouh et al., 2023). Strategic planning involves long-term decisions such as facility location, districting of service areas, capacity planning, and annual demand forecasting. Tactical planning encompasses medium-term decisions including aggregate demand forecasting, admission planning, resource dimensioning, and the assignment of staff to patients. Operational planning, which has been more extensively studied in previous reviews, mainly focuses on short-term scheduling and routing of caregivers.

The review by Chabouh et al. (2023) emphasizes strategic and tactical planning issues, identifying seven principal research themes: network design, capacity planning, demand planning, admission planning, resource dimensioning, assignment, and risk management. Among these, network design has emerged as the most extensively studied and developed area.

Network design has primarily focused on locating home healthcare facilities and assigning service areas through districting. Most studies in this area rely on deterministic mixed-integer programming models, although a few recent contributions have integrated uncertainty and incorporated multi-objective goals (Shiri et al. (2023) and Shiri et al. (2021)). Some approaches also combine location decisions with staff assignment and routing considerations. Capacity planning has received very limited attention overall, with only one notable study by Zheng et al. (2021) developing a stochastic programming model that jointly determines the number of staff and service authorization policies under uncertain demand. As a result, this area remains largely unexplored. Demand planning is also relatively scarce, with only five studies (Hare et al. (2009), Cardoso et al. (2012), Lanzarone et al. (2010), Argiento and Guglielmi (2016) and Argiento et al. (2017)) addressing the forecasting of annual or aggregate demand using methods such as Markov models and simulation. These contributions mainly focus on projecting patient numbers and transitions between care settings, while few explicitly consider uncertainty in demand evolution. Admission planning has also been rarely studied with just two papers (Koeleman et al. (2012) and De Angelis (1998)) examining how to admit patients from waiting lists while respecting specific rules as well as resource and budget constraints; among them, one employed stochastic programming and the other used Markov chains. Resource dimensioning has been addressed in eight studies (Lin et al. (2018), Nasir et al. (2018), Restrepo et al. (2019), among others), typically in combination with other decisions such as location or assignment, and has mostly focused on determining staffing levels, although some works have included medical devices and supplies. Occasionally, uncertainty in demand or workloads has been incorporated into these models. Assignment represents the most extensively researched tactical area with many studies integrating staff assignment with routing and scheduling to address objectives such as workload balancing, continuity of care and minimizing overtime, often while accounting for uncertainty (Hertz and Lahrichi (2009), Lanzarone et al. (2012), among others). Finally, a few studies on risk management have mainly focused on accounting for disruptive events that may result in interruptions of the service such as natural disasters, pandemics or uncertainty in operations, emphasizing the assessment and mitigation of their impact on care delivery (Guinet et al. (2017), Barkaoui et al. (2018), among others).

A few studies explicitly incorporate uncertainty and multiple objectives. For example, Shiri et al. (2023) proposed a multi-objective two-stage stochastic model that integrated facility location with staff assignment, routing, and scheduling under variability in service times and demand. Similarly, Nikzad et al. (2020) developed a two-stage stochastic mixed-integer programming framework that combines districting with resource dimensioning and assignment scheduling, demonstrating how complex interdependencies can be addressed within a single model. These contributions are particularly relevant as they represent some of the few efforts to jointly address network design and capacity planning within a unified framework. Nevertheless, while these models advance methodological complexity, the integration of digital health technologies—particularly telemonitoring—into network design remains largely absent from the literature.

Building on these insights, this thesis develops an integrated optimization model that combines network design and capacity planning to support the implementation of telemonitoring-enabled home healthcare services. It contributes to the literature by integrating telemonitoring, which remains largely unexplored in optimization-based planning models, and by combining location decisions with capacity dimensioning, an area in which only a limited number of studies have gone beyond single-objective models. In particular, the model incorporates a bi-objective approach to balance cost efficiency and capacity maximization, while also introducing, lexicographically, a third auxiliary objective to account for geographic coverage, i.e., the number of demand points that the network can reach. To be more specific, rather than incorporating explicit demand volumes, the model considers a set of geographic areas from which demand may arise and determines whether service can be feasibly provided to each location given the network configuration. By identifying which geographic areas can be served by which units and defining their capacity while addressing resource utilization and allocation of additional clinical staff, the model aims to offer a comprehensive framework for planning technology-enabled care delivery. It also provides a foundation for rethinking how digital health interventions can be integrated into HH, as explored in the following section.

6 Methodology

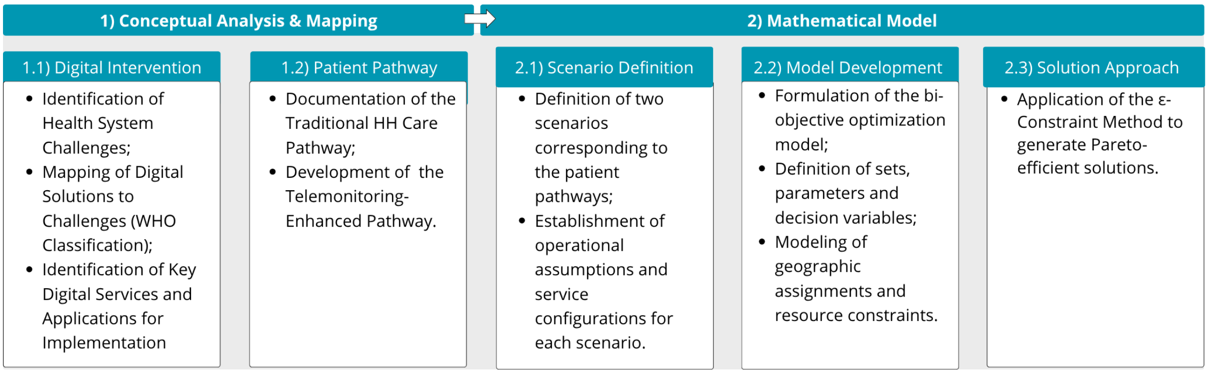

Figure 1: Methodology Overview.

Figure 1 presents an overview of the methodology adopted which is organized into two main phases. The first establishes the conceptual basis by analysing how digital health interventions can address existing challenges in HH and by defining reference patient pathways for the two different care delivery models (section 6.1). The second phase involves the development of a mathematical model designed to quantitatively evaluate and optimize the impact of integrating telemonitoring into these services (section 6.2).

6.1 Conceptual Analysis & Mapping

The first phase was essential for establishing a conceptual understanding of how digital health interventions could enhance HH services in the Portuguese context. To this end, a structured mapping was first developed, linking previously identified health systems challenges with corresponding digital health interventions, based on the *Classification of Digital Health Interventions, Services, and Applications in Health* (CDHISAH) (World Health Organization, 2023). This classification provides a standardized framework that describes how different digital technologies, organized into four groups based on the targeted primary user – persons (patients, potential patients and caregivers), healthcare providers, health system managers and data services – address specific challenges related to access, quality and efficiency, contributing to a shared language for planning and evaluation.

The mapping process involved three main steps. First, key challenges affecting HH implementation and scaling in Portugal were compiled. Second, these challenges were aligned and associated with the standardized health system challenge categories described in the CDHISAH. This step required interpreting and matching context-specific issues to the broader framework categories to ensure consistency and comparability. Since the framework lists challenges, interventions, and digital service categories separately rather than specifying direct links among them, a third step was undertaken to systematically associate each challenge category with the interventions and service types considered most relevant for addressing it. This analysis resulted in a comprehensive matrix of potential solutions tailored to the HH context.

The figure presented in Appendix A illustrates this mapping. On the left, the identified challenges from existent literature and their alignment with WHO's standardized challenge categories are displayed, while the middle columns show the selected interventions – color-coded according to their targeted primary user group – and the right columns list the digital services and applications prioritized as enablers of HH transformation. For example, the identified challenge "Lack of 24-hour supervision" was associated with the WHO Health System Challenge Inadequate supportive supervision (3.6). This challenge was then linked to two Digital Health Interventions: Remote monitoring of person's health (2.4.2) and Self-monitoring of health (1.4.2). Each of these interventions was subsequently associated with specific digital services and applications, including telehealth systems (A9), personal health records (A7) and health management information systems (D6), which together enable continuous monitoring and timely clinical decision-making.

To illustrate the conclusions of this mapping, the resulting services and application types are summarized in Figure 2.

Services and Application Types

A1	Communication systems	Systems that can be used to transfer electronic information. Messages can be exchanged between healthcare providers or between healthcare providers and persons.
A3	Decision support system	Computer-based tool which combines medical information databases and algorithms with patient-specific data.
A5	Electronic medical record systems	Secure system that holds information about people's health and clinical care and is managed by healthcare providers.
A7	Personal health records	Digital personal health record that registers an individual's health information like a patient portal.
A9	Telehealth systems	Electronic information and telecommunication technologies that allow monitoring and/or delivery of healthcare to patients at remote locations far from where the healthcare provider is.
B4	Human resource information systems	Systems that support tracking, management and planning of the healthcare workforce.
B5	Learning and training systems	Case log system that can be accessed by healthcare professionals.
B7	Patient administration systems	Systems that support the management of administrative and logistical processes related to patient care.
C5	Health worker registry	Central authority for maintaining the unique identities of healthcare providers within a country.
C6	Identification registries and directories	Proof of legal identity; enables a person to prove who they are by using credentials recognised by law.
D1	Analytics systems	Data tools to facilitate decision-making processes: dashboards, data visualisation etc.
D2	Data interchange and interoperability	Software capabilities to support managed data exchange and interoperability between applications and services.
D5	Geographic information systems (GIS)	Analyses and displays geographically referenced information.
D6	Health Management Information Systems (HMIS)	Performance management to increase the quality of health services.
E1	Emergency preparedness and response systems	Systems that help manage knowledge and resources to anticipate, respond to, and recover from disasters.

Figure 2: Summary of Services and Application types.

Given this, the results can be organized into the four primary target groups defined by the framework, highlighting how different services and applications contribute to integrating telemonitoring in Home Hospitalization while addressing the main challenges identified in the Portuguese context. For persons, systems such as communication systems (A1), personal health records (A7), and telehealth systems (A9) enable patients to engage in self-monitoring, communicate remotely with healthcare providers and access their own health information, supporting continuous connection with the care team. These capabilities directly help mitigate the lack of 24-hour supervision by allowing remote monitoring and immediate communication, and they reduce caregiver burden by empowering patients to participate more actively in their care. For healthcare providers, decision support systems (A3), electronic medical record systems (A5) and learning and training systems (B5) enhance the capacity to monitor patients at a distance, receive timely alerts and make informed clinical decisions based on up-to-date data. These tools are critical to overcome technological limitations by standardizing information flows and ensuring providers can respond effectively to patient needs, while also addressing the challenges of underdeveloped workflows and supporting the ongoing training needed to counter workforce shortages and demotivation.

For system managers and support personnel, solutions like human resource information systems (B4), patient administration systems (B7), health worker registry (C5), identification registries and directories (C6) and emergency preparedness and response systems (E1) facilitate the planning, coordination and scaling of telemonitoring services. In practice, these applications support better allocation of scarce human resources, improve processes for screening and recruiting suitable patients and enhance readiness to respond to fluctuating demand. Finally, for data services, components such as analytics systems (D1), data interchange and interoperability (D2), geographic information systems (D5) and health management information systems (D6) enable the integration, analysis and use of telemonitoring data to guide management, planning, and evaluation across the health system. This contributes to solving fragmented information flows and ensuring that telemonitoring supports equitable access by identifying geographic gaps and facilitating remote care delivery where physical infrastructure is limited.

These interventions have been implemented successfully in some health systems, providing practical evidence of their potential. For example, the NHS (National Health Service) Virtual Wards in England combine remote monitoring technologies, teleconsultations, and access to personal health information to deliver acute care in patients' usual place of residence, supported by digital platforms that allow continuous observation of vital signs and integration with electronic patient records across all regions served (NHS England, 2024). In Australia, the National Digital Health Strategy has driven widespread use of My Health Record, which now covers over 23 million people and is connected to systems including electronic prescribing, secure messaging, and telehealth services. These capabilities enable near real-time information sharing among healthcare providers and all patients, improving continuity of care and supporting digitally enabled models like HH (Australian Digital Health Agency, 2023). These two successful examples illustrate that the proposed solutions resulting from this analysis are not only theoretically aligned with WHO's framework but are already delivering tangible benefits internationally.

Building on this information, two process diagrams were developed and are presented in Figures 3 and 4, illustrating the patient pathway for Home Hospitalization with and without telemonitoring.

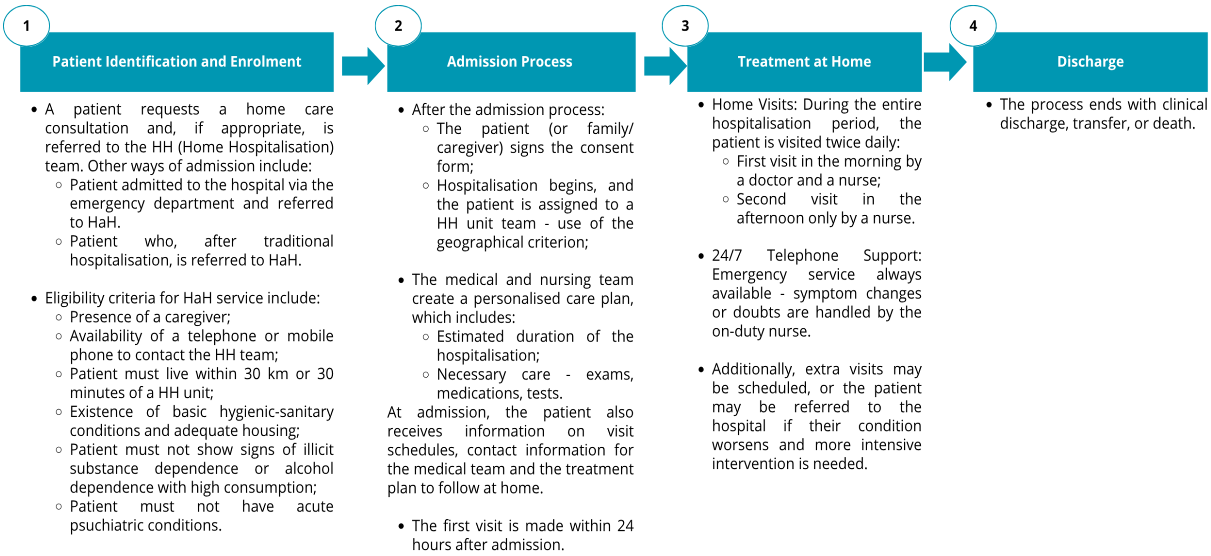

Figure 3: HH Patient pathway without telemonitoring.

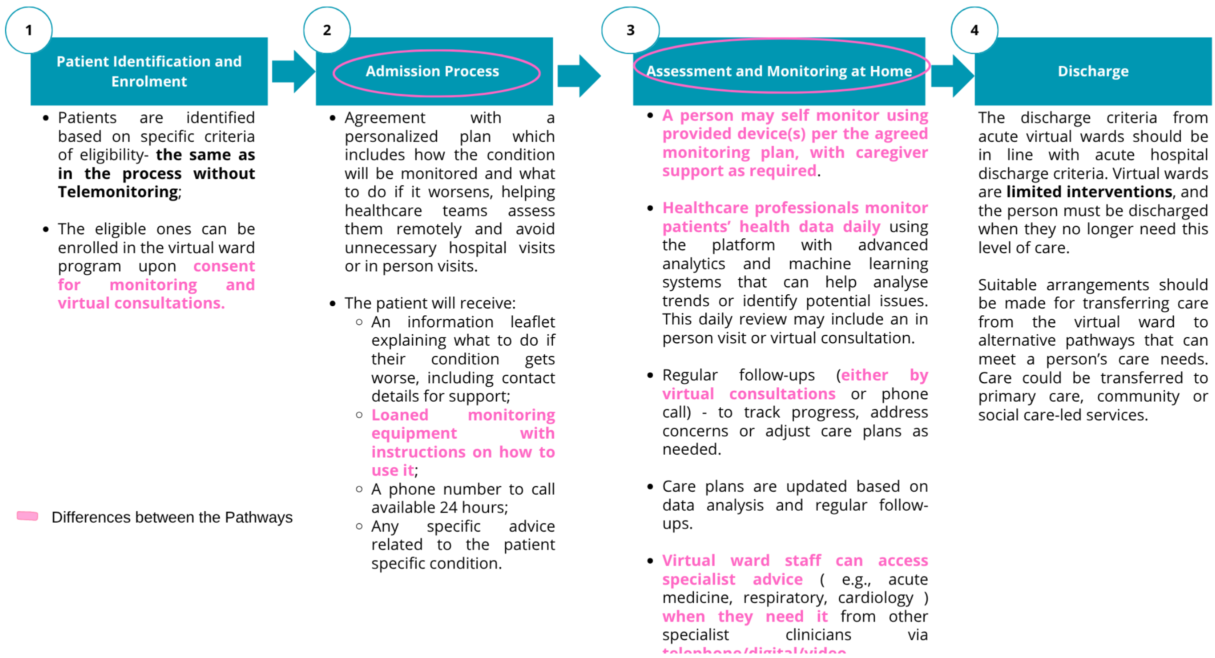

Figure 4: HH Patient pathway with telemonitoring.

The traditional model (Figure 3), based on the guidelines published by the Directorate-General of Health (DGS) (DGS, 2018), involves patient identification and enrolment based on clinical eligibility, followed by in-person admission and treatment managed by the HH team. Care delivery consists primarily of scheduled home visits—typically two per day—conducted by doctors and nurses, alongside 24/7 telephone support. Clinical decisions are mainly made based on observations during these visits, with little or no information about the patient's condition in between. In contrast, the pathway with the inclusion of telemonitoring (Figure 4) is based on insights from the NHS England Virtual ward example (NHS England, 2023b) and supported by more general perspectives on virtual care (HETTShow, 2024). The eligibility criteria are the same, but this pathway introduces telemonitoring from the point of enrolment during which patients and caregivers provide consent for digital monitoring and are equipped with devices, instructions, and support contacts. Care is guided by a personalized monitoring plan, enabling patients to self-monitor while healthcare professionals remotely track health data daily through analytics platforms. Follow-ups can occur via virtual consultations or phone calls, with clinical decisions based on continuous data assessment. This model includes structured escalation protocols and facilitates remote specialist input through digital means.

Overall, this conceptual study lays the groundwork for the development of the mathematical model presented in the subsequent section.

6.2 Mathematical Model

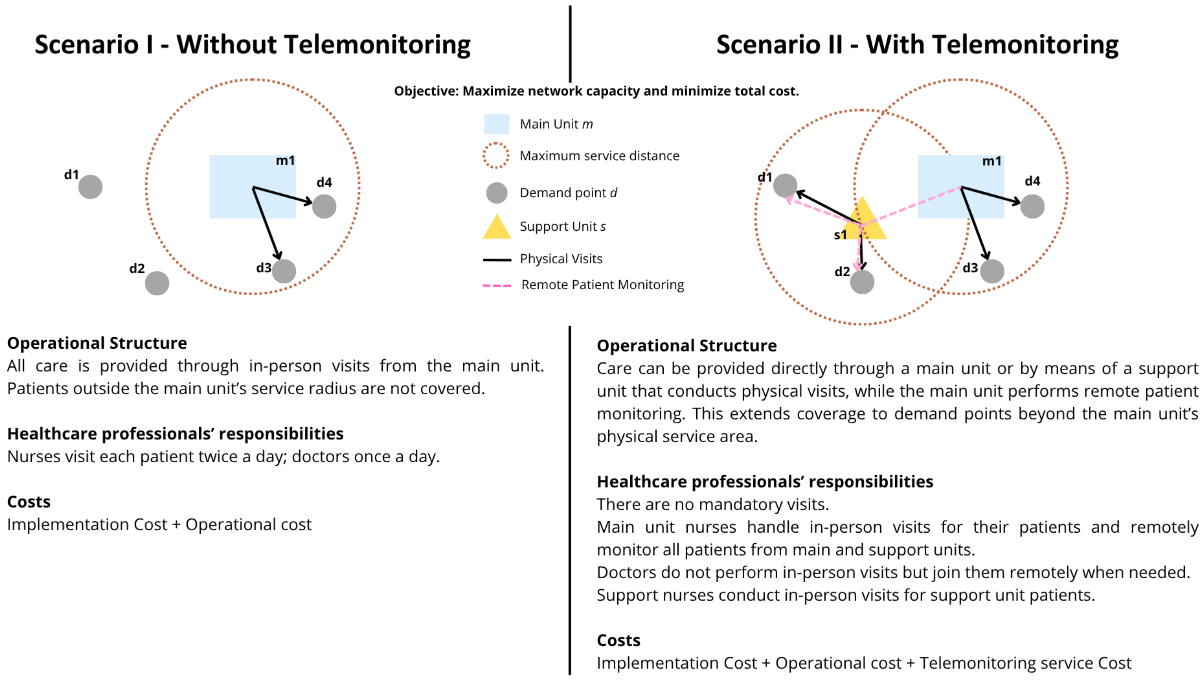

Figure 5: Care Delivery Scenarios.

Following up on the conceptual mapping of patient pathways and digital interventions outlined in the previous section, a mathematical programming model to quantitively evaluate the operational impact of integrating telemonitoring into HH services was developed. To do so, two care delivery scenarios were defined and modelled to reflect the two pathways previously mentioned. These scenarios are visually summarized in Figure 5.

Scenario I mirrors the current practices observed in HH programs in Portugal. All patient care is delivered exclusively through physical visits conducted by healthcare professionals based at the main hospital unit. Geographic coverage is constrained to patients located within a defined service distance, limiting the potential reach of HH services. As it was mentioned, care activities are mostly done in planned in-person visits which requires a planned scheduled that normally includes two visits per day per patient, one by both a doctor and a nurse and the other by a nurse. This approach requires a high level of resources and limits the flexibility and ability to scale the service, especially in areas with spread-out population or shortage of healthcare professionals, plus it also excludes patients who live further away than the maximum distance of service. These factors contribute to unequal access to this type of care delivery service across different regions.

Scenario II introduces a telemonitoring-enhanced model that builds upon the digital health solutions and the patient pathway explained in the previous section. In this configuration, patients may be served in two different ways: directly – the main unit is fully responsible for attending to the patient needs – or indirectly – the main unit is responsible for the remote monitoring activities, while a designated support unit conducts the in-person visits. In both, the main unit is always responsible for remote patient monitoring, leveraging digital tools such as wearable devices and real-time data analytics platforms which allows patient follow-up to be partially and, in some cases, fully conducted remotely. The connection between the main and support units is defined by geographic proximity, both to ensure coordinated care and because, in exceptional situations, it may be necessary for a doctor from the main unit to travel in person. As a result, the frequency of in-person visits can be reduced and the geographical reach of the service can be extended.

Healthcare professionals' roles are also adapted according to this new model of care. Nurses' responsibilities are differentiated between in-person visits – handled by support and main unit nurses and remote monitoring – handled exclusively by main unit nurses. As for doctors, whose clinical responsibilities involve diagnostic interpretations, defining the treatment plan and prescribing or adjusting medication are no longer required to attend in-person visits. Instead, they can provide clinical input remotely by reviewing patient data collected through monitoring devices and conducting teleconsultations, often synchronously with a nurse on-site when needed. Cost wise, this scenario introduces an additional component alongside the implementation and operational costs – the telemonitoring service cost. It is defined as the cost associated with the digital infrastructure and continuous data management require to support remote patient monitoring.

This section outlines the mathematical formulation of Scenario II. Although both scenarios were modelled to support the evaluation of the added value introduced by telemonitoring, Scenario II represents the core focus of this research and the innovative pathway for the service transformation. The mathematical formulation for Scenario I is presented in Appendix B.

6.2.1 Sets

Table 1: Sets.

Sets	
$d \in D$	Set of demand points
$m \in M$	Set of potential main units
$s \in S$	Set of potential support units
$SM = \{(s, m) \in S \times M: dist_{sm} \leq D_{link}\}$	Set of feasible support-main unit pairs such that the distance between support unit s and main unit m does not exceed the maximum allowable distance

6.2.2 Parameters

Table 2: Parameters.

Parameters	
$t_{visit}(minutes)$	Average visit time
$t_{call}(minutes)$	Average call time
$t_{tele}(minutes)$	Average duration that a doctor allocates to a tele appointment per patient
$V\ (fraction)$	Average number of visits per patient per day
$C\ (fraction)$	Average number of calls per patient per day
$T\ (fraction)$	Average number of tele appointments per day
$A\ (fraction)$	Average physiological alerts per patient per day
$D_{max}\ (km)$	Maximum service distance between a main or support unit and a demand point d
$D_{link}\ (km)$	Maximum distance between linked main and support units
$v\ (km/h)$	Average travel speed
$Y\ (days)$	Number of days in one year
$H\ (hours)$	Number of hours in one shift

Parameters

$\overline{N}_m$	Number of nurses available at main unit m
$\overline{D}_m$	Number of doctors available at main unit m
$W^n(€)$	Hourly wage for nurses
$W^d(€)$	Hourly wage for doctors
$\alpha\ (fraction)$	Fraction of visits that require the intervention of a doctor
$\beta\ (fraction)$	Fraction of visits that require the intervention of a nurse
$K^I(€)$	Implementation cost per bed
$K^R(€)$	Annual running cost per bed
$K^T(€)$	Annual telemonitoring service cost
$dist_{dm}(km)$	Spherical distance from demand point d to main unit m
$dist_{ds}(km)$	Spherical distance from demand point d to support unit s
$dist_{sm}(km)$	Spherical distance from support unit s to main unit m
t_{travel}[3]$(minutes)$	Average time to travel between any two points within a D_{max} radius at a v speed

6.2.3 Decision Variables

Table 3: Decision Variables.

Primary Decision Variables

$X_{dm} \in \{0, 1\}$	Equals 1 if demand point d is assigned to main unit m; 0 otherwise.
$Y_{ds} \in \{0, 1\}$	Equals 1 if demand point d is assigned to support unit s; 0 otherwise.
$Y_{sm} \in \{0, 1\}$	Equals 1 if support unit s is linked to main unit m; 0 otherwise.
$P_m \in \mathbb{Z}$	Number of available beds directly served by main unit m.
$N_m \in \mathbb{Z}$	Number of nurses at main unit m.
$D_m \in \mathbb{Z}$	Number of doctors at main unit m.
$P_{ms} \in \mathbb{Z}$	Number of available beds monitored by main unit m and served by support unit s.
$N_s \in \mathbb{Z}$	Number of nurses at support unit s.

[3] $t_{travel} = \frac{\frac{128 \times D_{max}}{45\pi}}{v}$

Table 4: Auxiliary Decision Variables.

Auxiliary Decision Variables

$Z_m \in \{0, 1\}$	Equals 1 if main unit is open; 0 otherwise.
$W_d \in \{0, 1\}$	Equals 1 if demand point d is served (either directly or indirectly); 0 otherwise.

6.2.4 Objective Function

Objective 1: Maximize Capacity

This objective aims to maximize the total available capacity of the home hospitalization network considering both the beds that are directly served by each main unit as well as the beds that are remotely monitored by a main unit but physically served by a support unit.

$$max\ Q = \sum_{m\in M} P_m + \sum_{m\in M} \sum_{s\in S} P_{ms} \tag{1}$$

Objective 2: Minimize Costs

This objective aims to minimize the total annual cost of operating the home hospitalization network. It comprises the per-bed implementation, operational and telemonitoring service costs as well as the costs with all resources.

$$\begin{aligned} \min \mathrm{C} = \sum_{m\in M} (P_m + \sum_{s\in S} P_{ms}) \times (K^I + K^R + K^T) + \sum_{s\in S} N_s \times W^n \times H \times Y + \\ + \sum_{m\in M} D_m \times W^d \times H \times Y + \sum_{m\in M} N_m \times W^n \times H \times Y \end{aligned} \tag{2}$$

Auxiliary Objective: Maximize Geographical Coverage

This objective aims to maximize the number of demand points that can be served by the network.

$$max\ G = \sum_{d\in D} W_d \tag{3}$$

6.2.5 Constraints

Geographic Assignment

Constraints (4) to (6) enforce geographic feasibility by limiting assignments to within the maximum allowable service distance. Constraints (4) ensures that a demand point d can only be assigned to a main unit m if it falls within the maximum distance threshold D_{max} and, in that case, the main unit is considered to be open. Constraints (5) enforces that no assignment to a main unit is possible if the distance exceeds this threshold. Similarly, constraints (6) restrict assignment to support units, making them unavailable to demand points located beyond D_{max} .

$$X_{dm} = Z_m, \ \forall d \in D, m \in M : \ dist_{dm} \ \leq D_{max} \tag{4}$$

$$X_{dm} = 0, \ \forall d \in D, m \in M : \ dist_{ds} \ > D_{max} \tag{5}$$

$$Y_{ds} = 0, \ \forall d \in D, s \in S : \ dist_{ds} \ > D_{max} \tag{6}$$

Constraints (7) define the activation rule for the binary variable W_d, which equals 1 if demand point d is served. In scenarios with telemonitoring, a demand point is considered covered if it can be served either by a main unit or by means of a support unit.

$$W_d \leq \ \sum_{m \in M} X_{dm} + \sum_{s \in S} Y_{ds} \ , \ \forall d \in D \tag{7}$$

Support – Main Unit Linking

Constraints (8) enforces that each support unit is linked to at most one main unit.

$$\sum_{m \in M:(s,m) \in SM} Y_{sm} \leq \ 1, \ \forall s \in S \tag{8}$$

Constraints (9) ensures that a support unit can only be linked to a main unit if it is serving at least one demand point.

$$\sum_{m \in M:(s,m) \in SM} Y_{sm} \leq \ \sum_{d \in D} Y_{ds} \ , \ \forall s \in S \tag{9}$$

Constraints (10) ensures that a demand point can only be assigned to a support unit if the support unit is linked to a main unit.

$$Y_{ds} = \ \sum_{m \in M:(s,m) \in SM} Y_{sm}, \ \forall s \in S, d \ \in \ D \ : \ dist_{dm} \ \leq D_{max} \tag{10}$$

Flow Activation (Big-M)

Constraints (11) and (12) regulate the activation of patient flow through main units. Constraints (11) ensures that a demand point is only served by a main unit if that main unit has capacity for at least one bed. Constraints (12) reinforces that beds can only be allocated if the main unit is open, using a Big-M formulation to deactivate capacity when it is not.

$$X_{dm} \ \leq P_m, \ \forall d \ \in \ D, \forall m \in M \tag{11}$$

$$P_m \ \leq BigM \ \times Z_m, \ \forall m \in M \tag{12}$$

Constraints (13) to (15) set the rules for the activation of support units. Constraints (13) and (14) function together to guarantee that for beds to be allocated to a support unit there must be a support unit-main unit valid link and vice versa.

$$P_{ms} \geq Y_{sm}, \ \forall m \in M, \forall s \in S: (s,m) \in \ SM \tag{13}$$

$$P_{ms} \leq BigM \ \times Y_{sm}, \ \forall m \in M, \forall s \in S: (s,m) \in \ SM \tag{14}$$

Finally, constraints (15) ensures that no capacity is allocated to infeasible support-main unit links.

$$P_{ms} = 0, \ \forall (s,m) \ \notin SM \tag{15}$$

Capacity Constraints

A. Main Unit Nurses' Workload

Constraints (16) ensures that the total workload assigned to nurses at a main unit does not exceed their available working time. This includes:

- Monitoring patients assigned directly to the main unit m.
- Monitoring patients in support units.
- Visiting patients assigned to the main unit.

$$P_m \times t_{mon} + \sum_{s \in S} P_{ms} \times t_{call} \times (C + A) + P_m \times V \times \beta \times (t_{visit} + t_{travel}) \leq N_m \times H \times 60, \forall \, m \in M \tag{16}$$

An underlying assumption of this model is that these services are already in place and that the resources are already allocated to each main unit. Plus, there is no intention in hiring additional staff since one of the objectives is to scale the service and improve resource utilization within this new care model. As such, Constraints (17) limits the maximum available nurses for all tasks require to the ones already hired to the main unit in question $\overline{N}_m$. For this scenario, one of the nurses from the main unit must be dedicated full-time to monitoring patient data, ensuring the continuous supervision of the telemonitoring system.

$$N_m \leq \overline{N}_m - 1, \ \forall m \in M \tag{17}$$

B. Doctors' Workload

Constraints (18) ensures that the total workload assigned to doctors at the main unit does not exceed their available working time. This workload includes the time spent conducting tele-appointments with patients served directly by the main unit as well as those monitored remotely through it.

$$P_m \times V \times \alpha \times t_{tele} + \sum_{s \in S} P_{ms} \times V \times \alpha \times t_{tele} \leq D_m \times H \times 60,\ \forall m \in M \quad (18)$$

Constraints (19), based on the same assumption of Constraint (17), limits the number of doctors that can be assigned to each main unit to the existent number of doctors already hired for the Home Hospitalization service of that facility.

$$D_m \leq \overline{D}_m,\ \forall m \in M \quad (19)$$

C. Support Unit Nurses' Workload

Constraints (20) ensures that the total time required to visit patients assigned to support unit s does not exceed the total working time available from the nurses at support unit s. Unlike the service in the main units, this activity represents a new extension of the care network which implies hiring additional staff, since no equivalent service is currently in place at the support units.

$$\sum_{s \in S} P_{ms} \times V \times \beta \times (t_{visit} + t_{travel}) \leq N_S \times H \times 60,\ \forall s \in S \quad (20)$$

6.3 Solution Approach

In real planning environments, decision-makers often face multiple conflicting objectives. While combining these multiple objectives into a single objective function is possible, this approach can oversimplify trade-offs and fail to represent the decision-maker's true interests (Mesquita-Cunha et al., 2023)

In contrast, multi-objective optimization problems (MOOPs) are designed to handle this complexity by simultaneously optimizing more than one objective, obtaining a set of non-dominated solutions, known as the Pareto optimal set or Pareto Front – a representation of the trade-off curve between the different objectives – which allows for more informed decision about which solution to choose. In other words, a solution is considered Pareto optimal or non-dominated if no other feasible solution can improve one objective without worsening at least one other, and the collection of such solutions forms the Pareto front.

The model developed is a multi-objective optimization problem (MOOP) that balances two conflicting goals: maximizing the capacity of the home hospitalization service and minimizing total cost. Improving capacity typically requires additional investment, creating a natural trade-off.

To solve MOOPs in large-scale problems, the ε-Constraint Method is commonly used, as it can generate both supported and unsupported efficient solutions and does not require scaling (Mavrotas, 2009). The ε-Constraint Method generates the Pareto front by transforming a multi-objective problem into a sequence of single-objective problems: one objective for optimization, while the others are converted into constraints bounded by the ε parameter which is varied to produce a diverse set of solutions and thus approximate the Pareto Front**.** Its main limitation is that it requires some previous knowledge pertaining to how this parameter should vary.

Bérubé et al. (2009) proposed an algorithm to generate the Pareto front of bi-objective optimization problems using the ε- Constraint Method. It first determines the ideal and nadir points—representing the best and worst values among efficient solutions—using lexicographic optimization. The process involves optimizing each objective independently and then re-optimizing the other objective while holding the first at its optimal value.

In the context of this study, the procedure involves first finding the maximum achievable capacity of the network and then determining the minimum cost required to maintain that capacity. The process is subsequently reversed: the total cost is minimized independently, and then the highest capacity achievable at this minimum cost is identified. These two reference points establish the bounds of the objectives: the ideal value corresponds to the best observed level of an objective (e.g., the maximum capacity or the minimum cost), while the nadir value represents the worst level observed for that objective across the efficient solutions (e.g., the lowest capacity found when minimizing cost). Once these reference points are established, one objective—in this case, capacity—is selected to act as a constraint. The ε parameter is initially set at the nadir value for capacity and is progressively increased in fixed steps toward the ideal value. This generates a sequence of solutions that illustrate different trade-offs between maximizing capacity and minimizing costs.

7 Data Collection

Following the methodology previously outlined, this chapter details the input data used in the model, including sources and assumptions used to estimate specific parameter values.

7.1 Network

CUF is one of Portugal's largest private healthcare networks, managing a network of hospitals, clinics and health centers across the country. Among CUF's services is the Home Hospitalization Unit which delivers hospital-level care in the patient's own home. This service started in June 2020 in the Lisbon Metropolitan Area (LMA). The service includes a team of health professionals who ensure care continuity and safety, operating every day, 24 hours a day.

Given this, the network – set of main units (Appendix C), demand points (Appendix D) and support units (Appendix E) – applied to the model was based on CUF's existent facilities in the LMA. Figure 6 depicts the network resorting to the Google Maps tool MyMaps.

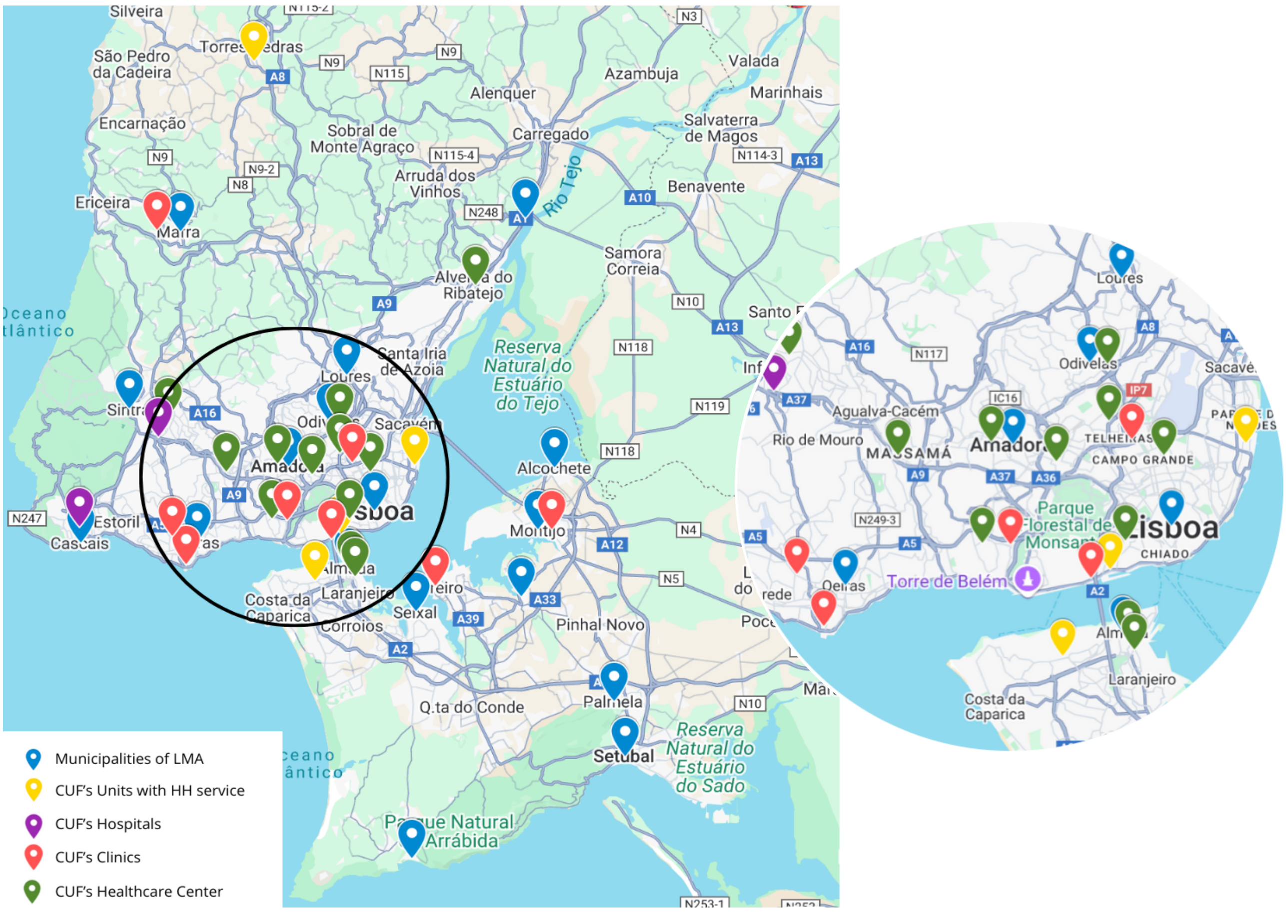

Figure 6: Model's HH Network.

The main units correspond to the four CUF units in which HH services are already implemented. As for the demand points, the 18 municipalities of LMA were considered. Lastly, for the support units, all other CUF's facilities in the LMA were considered, including three different types of facilities: hospitals, clinics and healthcare centers.

Based on the geographical coordinates of the locations, the distances between them were calculated, obtaining parameters: $dist_{dm}(km)$, $dist_{ds}(km)$ and $dist_{sm}(km)$. The calculation used the Haversine formula, which estimates the shortest path between two points along the Earth's curvature. To account for real-word distances being longer than straight-line estimates due to street layouts, the calculated distances were multiplied by a circuity factor, c, assumed to be 1.25. This estimate, drawn from Costa et al. (2021), better approximates travel distances in Lisbon's urban context by incorporating the average detour ratio cause by the street layout.

Additionally, D_{max} (km) was set at 30 km in line with the eligibility criteria stated in Figure 3. Similarly, D_{link} (km) was also set at 30 km to expand the coverage area without extending it to a point that could hinder coordination or timely intervention from the main unit.

7.2 Costs

Table 5: Cost Parameters.

Parameters		Parameters	
$K^I(€)$	77 481.84€	$W^n(€)$	16.32€
$K^R(€)$	31 500€	$W^d(€)$	23.50€
$K^T(€)$	2 693.70 €		

The estimation of the cost parameters is presented in Table 5. The implementation costs, K^I, associated with establishing the HH network were estimated from a newspaper article which reported that the implementation of a HH network with 413 beds entailed an investment of approximately €32 million (Sanches, 2025). To estimate the cost attributable to a single HH bed, the total amount was proportionally divided by the number of beds:

$$\frac{\text{Cost of Investment HH Network}}{\text{Number of beds HH Network}} = \frac{32\ 000\ 000\ €}{413} \approx 77\ 481.84€$$

Operational costs per bed, K^R, were calculated based on information provided by the SNS which indicates that the average cost of an HH stay with an average length of stay of 8 days is approximately €700 (SNS, 2016). From this value, to estimate the annual operational cost of a bed operating at full capacity, the following procedure was applied: the number of days in a year (365 days) was divided by the average length of a stay to determine the potential number of admissions per bed per year. This value was then multiplied by the average cost per stay. The result was an annual cost estimate of €31 500 per bed.

$$\text{Number of stays in a year} = \frac{\text{Number of days in a year}}{\text{Average length of stay}} = \frac{365 \text{ days}}{8 \text{ days}} \approx 45$$

$$\text{Operational Cost} = \text{Number of stays in a year } \times \text{Cost of a stay } = 45 \times 700€ = 31\ 500€$$

Annual telemonitoring service costs per bed, K^T, were retrieved from the results of the public procurement procedure led by the Shared Services of the Ministry of Health (Serviços Partilhados do Ministério da Saúde, SPMS), specifically Batch 1 – Telemonitoring Services (SPMS, 2015). Batch 1 defines the provision of telemonitoring services, including equipment installation and maintenance, a digital monitoring platform with alerts, patient training and support, data integration and regular reporting.

Lastly, hourly wages for resources, W^n and W^d were estimated based on publicly available information, more specifically, the Nursing Salary Table 2025 (SEP, 2025) and the Medical Salary Table 2025 (SIM, 2025), respectively. For the nurses' hourly wage estimate the hourly remuneration of specialist nurses was considered and an average between the lowest and highest pay grades was calculated.

$$W^n = \frac{22.10€/h + 10.55€/h}{2} \approx 16.32€/h$$

For the doctors' hourly wage estimate, the assumptions were similar. The hourly remuneration of an assistant graduate doctor was considered and an average between the lowest and highest pay grades was calculated.

$$W^d = \frac{22.27€/h + 24.87€/h}{2} \approx 23.50€/h$$

7.3 Workload

Workload parameters, presented in Table 6, include all information used to estimate the daily workload a resource has with one patient in a HH stay. For these estimates, besides CUF's provided data regarding the average time of a visit (t_{visit}) and the number of hours in a shift (H), two other sources were consulted: the SNS official benchmarking platform (SNS, 2025a) and a report of the implementation of a virtual ward (Health Innovation Network, 2021).

Table 6 : Workload Parameters.

Parameters		**Parameters**	
$t_{visit} (minutes)$	40	$A\ (fraction)$	2.50
$t_{call} (minutes)$	10	$\alpha\ (fraction)$	0.4048
$t_{tele} (minutes)$	40	$\beta\ (fraction)$	0.9716
$V\ (fraction)$	0.32	$v\ (km/h)$	50
$C\ (fraction)$	1.27	$H\ (hours)$	8
$T\ (fraction)$	0.32		

The average duration of teleconsultations (t_{tele}) was assumed equal to t_{visit} as doctors are expected to accompany patient visits remotely in the telemonitoring scenario. The parameter v was defined based on an assumption consistent with the guideline of an average unit-to-patient distance of 30 minutes, in the absence of published data. Indeed, when used as an input in the t_{travel} calculation, it results in a travel time of around 27 minutes.

From the case study evaluating the implementation and outcomes of a large-scale virtual ward model in Croydon, England, it was possible to estimate the values for t_{call}, V , C, T and A. Indeed, t_{call}, corresponds to the average duration of telephone contacts per patient per day, with the evaluation reporting an average of 1.27 calls per patient per day (C), reflecting the model's proactive approach to daily monitoring, even when no alerts were triggered. V indicates the average number of in-person visits per patient per day, registered as 0.32.As t_{tele} was defined to be equal to t_{visit}, under the assumption that doctors now conduct most patient contacts via teleconsultations, the parameter T was similarly established by assuming the same average frequency of teleconsultations per patient per day as observed for in-person visits. Additionally, A represents the average of physiological alerts per patient per day, reported to be 2.5, indicating readings outside normal limits that require intervention.

Lastly, resorting to SNS data it was possible to retrieve the distribution of HH visits by professional category. The results show that 2.8% of the visits are conducted by doctors, 58.8% by nurses, 37.2% are joined visits involving both and the remaining 1.2% were carried out by other healthcare professionals. However, the percentages were recalculated to include only doctors, nurses, and joint visits, excluding other professionals allowing to calculate α and β.

$$\alpha = Only\ doctor\ visits + Joint\ visits = \frac{2.8\% + 37.2\%}{2.8\% + 37.2\% + 58.8\%} = 40.48\%$$

$$\beta = Only\ nurses\ visits + Joint\ visits = \frac{58.8\% + 37.2\%}{2.8\% + 37.2\% + 58.8\%} = 97.16\%$$

7.4 Resource Availability

Resource availability estimates were based on data provided by CUF, which showed that each existent HH unit usually maintains a minimum allocation of one nurse and one doctor. However, to account for the need for dedicated monitoring, an additional nurse was added, resulting in a standard allocation of two nurses and one doctor per main unit. This staffing level was assumed uniform across all four main units.

8 Results and Discussion

8.1 Pareto Front Analysis

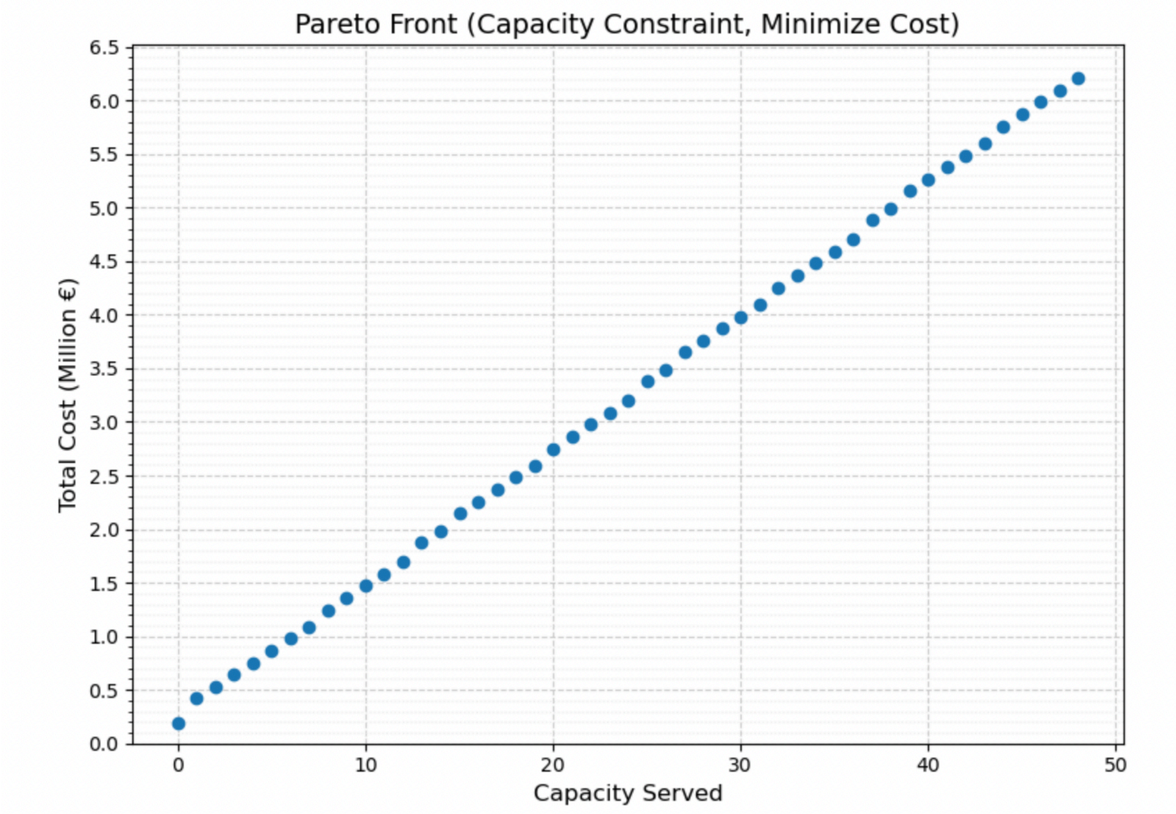

Figure 7: Pareto Front - Cost-Capacity Trade-off.

Figure 7 depicts the Pareto front obtained for the cost-minimization problem under capacity constraints. It illustrates the trade-off between the total cost and the number of patients served. Although the curve may appear linear, it follows a slightly concave trajectory, indicating a non-linear relationship between cost and capacity. As expected, total cost increases with higher service levels; however, the rate at which cost grows is not constant.

This broader non-linear behaviour becomes more apparent when examining the marginal cost per unit of capacity, shown in Appendix F. While many of the capacity intervals exhibit a consistent marginal cost of 111 675.54€ per additional patient – reflecting the standard incremental annual cost associated with operational and implementation expenses as well as telemonitoring service subscription, several segments deviate from this baseline.

These variations reflect structural shifts in the network configuration. Increases in capacity such as 7-8, 14-15, 19-20, 26-27, 31-32, 38-39 and 43-44 exhibit marginal costs of 159 329.94€, corresponding to the allocation of a support nurse to an existing support unit (47 656.4€), on top of the standard annual one-unit cost. More substantial cost increases are observed in the intervals 12-13, 24-25 and 36-37 in which marginal costs reach 180 295.54€.

These shifts are also linked to network reconfigurations, in this case, the deactivation of a support unit (resulting in the removal of the support nurse annual cost 47 656.4€) and the activation of a new main unit, requiring the additional annual cost of two nurses and one doctor (163 928.8€), again added to the incremental per-bed costs. It is important to note that the interval 0-1 stands out with the highest marginal cost of 227 949.94 €. This reflects the initial activation of the network, which requires setting up baseline infrastructure, in this case hiring the first main unit staff.

8.2 Comparison of Scenario I and Scenario II

To evaluate the added value of integrating telemonitoring into the HH care model, the results of Scenario I and Scenario II were obtained by running the baseline scenario, which considers all support units and assigns two nurses and one doctor to each main unit The results are presented in Table 7 side-by-side for comparison.

Table 7: Results Scenario I and II.

	Scenario I	**Scenario II**
Maximum Capacity	24	48
Cost	3 271 279.36 €	6 206 758.72 €
Cost per bed	136 303.31€	129 307.47€
Demand Points Served	14/18	18/18
Doctors at Main Units	4	4
Nurses at Main Units	8	8
Nurses at Support Units	-	4

In Scenario I, where the HH care model operates without telemonitoring, the system achieves a maximum capacity of 24 patients, at a total cost of approximately 3.27 million €. Conversely, Scenario II, which integrates telemonitoring technologies, reaches a maximum capacity of 48 patients at a total cost of approximately 6.2 million €.

When comparing these values, Scenario II achieves a 100% increase in capacity relative to Scenario I, meaning it serves twice as many patients. Moreover, this expansion results in an 89.75% increase in total cost, indicating that capacity grows at a faster rate than cost. In fact, the cost per bed in Scenario I is 5.41% higher, suggesting that telemonitoring not only enables broader service coverage, but it does so with a modest increase in cost-efficiency per patient served.

Resource wise, both scenarios make full use of the available staff at each main unit (M1, M2, M3 and M4): 2 nurses and 1 doctor. Regarding Scenario I all resources are responsible for in-person visits, directly delivering care to patient. In Scenario II, all main units still employ 2 nurses and 1 doctor, but one of the nurses is exclusively dedicated to monitoring patient data, overseeing all remote patient care only, while the other is responsible for the previously described tasks. In addition to this, 4 nurses are allocated to selected support units, in this case, units S4, S6, S8 and S13.

Nevertheless, this is not enough to truly comprehend the difference between these two scenarios, as it is also important to look at the geographic coverage – a critical factor in equitable access to care. Out of the 18 municipalities, in Scenario I only 14 can be served by the network, leaving out D7, D8, D17 and D18. Conversely, in Scenario II it is possible to serve all. While this may seem like a modest gain, it highlights the potential to expand service reach even with minimal additional resources. Indeed, the support units' nurses represent a staff increase necessary to expand geographic reach and patient capacity. Therefore, although Scenario II's solution entails a higher total cost, it not only increases overall system capacity at a better cost per bed but also improves equitable access to HH service, reinforcing its strategic relevance in addressing regional disparities.

To support this conclusion an additional scenario was modelled in which the telemonitoring-enabled system was constrained to serve the same number of patients as in Scenario I (24 in total). This intends to allow for a direct comparison between both configurations under the same capacity.

Table 8: Scenario II under Fixed Capacity of 24.

Capacity	**Cost**	**Cost per Bed**	**Demand Points Served**	**Doctors at Main Units**	**Nurses at Main Units**	**Nurses at Support Units**
24	3 198 688,16 €	133 278,67€	17/18	2	4	2

As presented in Table 8, the telemonitoring-based network achieved the same capacity at a lower total cost of approximately 3.1 million €, compared to 3.27 million € in Scenario I, reflecting a 2.22% cost reduction. This improvement in cost-efficiency is also reflected in the cost per bed, which falls from 136 303.31€ in Scenario I to 133 278,67€ with telemonitoring. In addition to these economic gains, the telemonitoring scenario achieved broader geographic coverage, successfully serving 17 out of the 18 demand points, while Scenario I was limited to 14. Furthermore, this outcome was accomplished while requiring significantly fewer resources: whereas Scenario I relied on four main units, each staffed with two nurses and one doctor, the telemonitoring configuration operated with only one nurse and one doctor at a single main unit (M1), supplemented by two support units (S6 and S21), each with one nurse.

These results support even further the operational efficiency introduced by telemonitoring, which enables a more streamlined, cost-effective, and geographically inclusive service model even under equivalent capacity constraints.

8.3 Sensitivity Analysis

8.3.1 Resource Levels

This section explores the sensitivity of the network to different levels of medical and nursing staff, aiming to evaluate whether these increases translate into capacity gains and to assess potential diminishing returns from resource expansion. As the baseline scenario represents the minimum feasible staffing—one doctor and two nurses per main unit—the analysis focuses exclusively on increasing resources, as reductions are operationally infeasible. This analysis is relevant given the workforce and budget constraints in the Portuguese healthcare system and is applied to both scenarios, as resource allocation and its impact on scalability differ between them.

Table 9: Impact of Resource Levels - Scenario I.

Varied Parameters		**Model Outputs**			
Max. Number of Doctors at Main Unit	**Max. Number of Nurses at Main Unit**	**Doctors Main Unit**	**Nurses Main Unit**	**Capacity**	**Cost**
1	3	1	2	24	3 271 279.36 €
	4				
	5				
2	3	2	3	36	5 044 159.04 €
	4		4	52	6 978 486.08 €
	5		4		
3	3	3	3	36	5 044 159.04 €
	4		4	52	6 978 486.08 €
	5		5	64	8 751 365.76 €

The results for the configuration without telemonitoring, presented in Table 9, reveal that system capacity is highly sensitive to staff availability, but only when the number of doctors and nurses is scaled together. While additional staffing generally improves capacity, this effect is not uniform. When only one doctor is available, increasing the number of nurses—from two to four or five—has no impact on capacity, which remains limited to 24 patients. This indicates a bottleneck driven by insufficient medical capacity. These scenarios, highlighted in red in Table 10, underscore that the limiting factor is not nursing capacity alone, but the imbalance between medical and nursing staff. Increasing the number of doctors to two, alongside a rise in nursing staff, results in a meaningful capacity improvement—from 24 to 52 patients. However, further increases in nurse availability without adjusting the number of doctors again does not increase capacity, reinforcing the same pattern. These findings highlight that doctors and nurses have interdependent but non-substitutable roles, and that scaling the HH network effectively depends on maintaining proportional increases across both categories.

Table 10: Impact of Resource Levels - Scenario II.

Varied Parameters		**Model Outputs**				
Max. Number of Doctors at Main Unit	**Max. Number of Nurses at Main Unit**	**Doctors Main Unit**	**Nurses Main Unit**	**Capacity**	**Cost**	**Support nurses**
1	3	1	3	100	12 395 122.00 €	5
	4		4	152	18 392 867.68 €	5
	5		5	176	21 263 698.24 €	5
2	3	2	3	100	12 395 122.00 €	5
	4		4	152	18 392 867.68 €	5
	5		5	200	24 409 008.80 €	5
3	3	3	3	100	12 395 122.00 €	5
	4		4	152	18 392 867.68 €	5
	5		5	200	24 409 008.80 €	5

When the same analysis is done considering the model with telemonitoring, the network presents a greater scalability with the same increase in main unit staffing. Across the range tested, capacity expands consistently as more doctors and nurses are added, without the early bottlenecks that appear on the configuration without telemonitoring. Importantly, this increase occurs while keeping the number of support nurses constant, suggesting that, for this range, the network can absorb significant capacity gains without additional support staff. Although this does not rule out possible constraints for other network dimensions, it reveals that telemonitoring enables a more flexible and scalable network structure, offering a greater margin for expansions before encountering resource bottlenecks.

8.3.2 Support Unit

Lastly, the impact of different support unit configurations on HH service delivery was examined through four progressively inclusive setups: (1) no support units, (2) hospitals only, (3) hospitals and clinics, and (4) hospitals, clinics, and healthcare centers. These variations aim to evaluate how the decentralization and diversification of support infrastructure can affect the HH service reach. This is particularly relevant in Portugal's context, where regional disparities in infrastructure availability can significantly affect implementation feasibility. The results for each scenario are presented in Table 11.

Table 11: Geographic Coverage under Different Support Unit Configurations.

Scenario	Maximum Capacity	Solution Cost	Demand Points Served	Support Units Used
1	28	3 782 630.32 €	14/18	0
2	38	4 994 694.52 €	14/18	S10 and S21
3	48	6206758.72 €	17/18	56, S10, S13 and S21
4	48	6206758.72 €	18/18	S4, S6, S8 and S13

The results show that the configuration and type of support units significantly affect both the capacity and geographic coverage of the HH network. In Scenario 1, with no support units, the system reaches a capacity of 28 and covers 14 out of 18 demand points. Scenario 2 introduces two hospital-based support units which are both used, increasing capacity to 38 but without improving coverage. Scenario 3 expands the network to include both hospitals and clinics, raising capacity to 48 and extending coverage to 17 points. Finally, Scenario 4 adds the healthcare centers, achieving full coverage without additional cost or capacity change.

This progression highlights the value of incorporating smaller, locally distributed support units such as clinics and healthcare centers. By being closer to patients, especially in underserved areas, these facilities improve the network's flexibility and reach. In regions like Portugal, where infrastructure availability varies widely, a diversified and decentralized support structure is key to ensure equitable access and effective implementation of HH services.

9 Conclusions, Limitations and Future Work

This thesis proposed and applied an integrated optimization model to support the design of a telemonitoring-enabled HH network. By combining network configuration and capacity planning into a multi-objective framework, the model allowed to assess trade-offs between cost and installed capacity as well as evaluate the impact of such solutions in terms of geographical reach. The model was applied to the LMA using CUF's existing infrastructure as a reference. The results led to the conclusion that integrating telemonitoring into HH services can significantly increase the capacity of the network, broaden its geographic coverage and lead to more cost-efficient solutions.

The most evident advantage of telemonitoring is the increase in service capacity. By enabling remote patient monitoring, reducing the need for in-person visits, this technology-enabled model of care allows healthcare professionals to follow more patients simultaneously. This operational shift alleviates the time constraints imposed by travel requirements, thereby enabling a more efficient use of healthcare resources. The model demonstrated that, under the same staffing levels, telemonitoring could double the number of patients treated at home.

Although the telemonitoring configuration introduces new cost components—such as the telemonitoring subscription service and additional support unit staff— it also allows for a more productive use of resources, especially at main units. The results showed that the additional cost is more than compensated by the increased capacity, as evidenced by a lower cost per bed relative to the traditional model.

Lastly, the results also show that the inclusion of telemonitoring enables the network to reach a larger number of municipalities, ensuring a more equitable access to the HH service. Through the integration of support units, whose staff becomes responsible for conducting local in-person visits when needed, while patients are remotely monitored by main units, the model enables the network to extend its services to municipalities that would otherwise fall outside the feasible range due to travel constraints.

Nevertheless, the model has some limitations that should be considered. First, data reliability is limited. Several parameters were estimated based on assumptions due to lack of concrete data, particularly regarding HH services integrating telemonitoring. Future work should prioritize the collection and integration of empirically validated, context-specific data from existing telemonitoring programs to strengthen the robustness of the model's assumptions.

Additionally, the model does not consider demand quantitatively, as this information does not yet exist. Instead, demand was represented by aggregated points and their geographical locations. This limits the model's ability to assign more capacity to areas with higher demand which could result in a less efficient resource allocation. Future research should conduct a detailed study of demand and incorporate it into models like this one to support more accurate planning and ensure resources can be better directed where they are most needed.

Furthermore, the model assumes that all support units are equal and operate independently, when CUF's facilities vary widely in size, equipment, staffing, and integration within the existing network. Ignoring these differences may lead to an inaccurate assessment of their true role and potential as support units. Future work should address this by incorporating unit-specific constraints and capabilities, ensuring a more realistic and operationally feasible network design.

In addition to these limitations, a relevant consideration emerged from the results regarding the distance between main and support units. An inadequate estimate could impact significantly the network configuration and capacity. Future work should explore the role of this parameter in more detail, aiming to obtain an evidence-based estimation.

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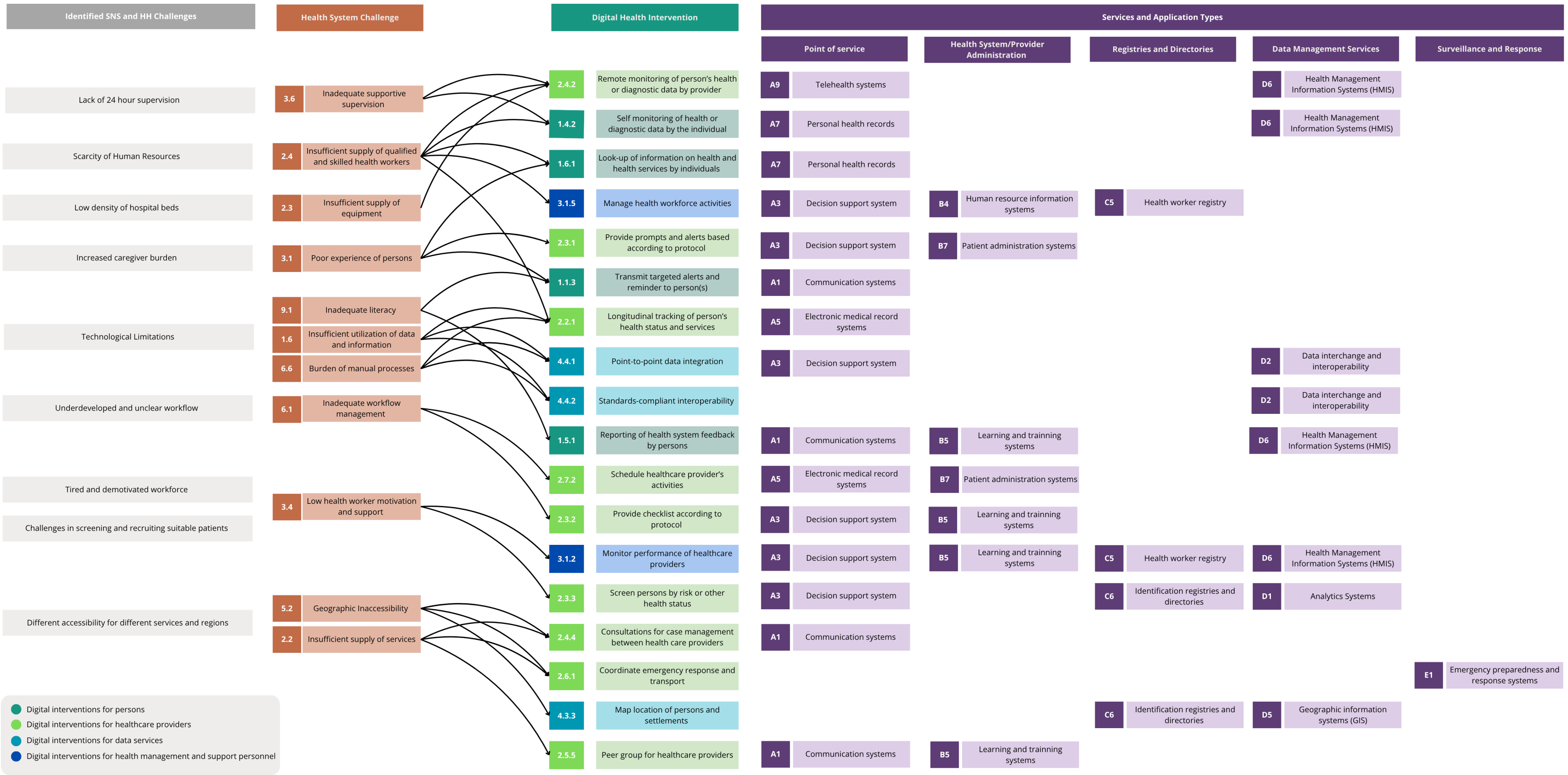
Appendices

Appendix A - Digital Services and Applications

This appendix provides an overview of the digital health services and applications considered in the study. It describes the main technological solutions used to support patient monitoring, communication, and care coordination within Home Hospitalization models.



Appendix B – Mathematical Model: Scenario without Telemonitoring

This appendix presents the mathematical formulation of the scenario without telemonitoring. It details the constraints and objective functions used to model the traditional Home Hospitalization configuration where patient follow-up is conducted exclusively through in-person visits.

Objective 1: Maximize Capacity

This objective aims to maximize the total available capacity of the home hospitalization network considering that beds are fully served by a main unit.

$$max\ Q = \sum_{m \in M} P_m \tag{21}$$

Objective 2: Minimize Costs

This objective aims to minimize the total annual cost of operating the home hospitalization network. It comprises the per-bed implementation and operational costs.

$$\min\ C = \sum_{m \in M} P_m \times ((K^I + K^R) + \sum_{m \in M} D_m \times W^d \times H \times Y + \sum_{m \in M} N_m \times W^n \times H \times Y \tag{22}$$

Auxiliary Objective: Maximize Geographical Coverage

This objective aims to maximize the number of demand points that can be served by the network.

$$max\ G = \sum_{d \in D} W_d \tag{3}$$

Geographic assignment

Constraints (4) ensures that a demand point dd can only be assigned to a main unit m if it falls within the maximum distance threshold D_{max} and, in that case, the main unit is considered to be open. Constraints (5) enforces that no assignment to a main unit is possible if the distance exceeds this threshold.

$$X_{dm} = Z_{dm},\ \forall d \in D, m \in M :\ dist_{dm} \leq D_{max} \tag{4}$$

$$X_{dm} = 0,\ \forall d \in D, m \in M\ dist_{dm} > D_{max} \tag{5}$$

Finally, Constraints (23) defines that for a demand point to be considered as served it must be assigned to at least one main unit.

$$W_d \leq \sum_{m \in M} X_{dm}\ \forall d \in D \tag{23}$$

Flow activation (Big-M)

Constraints (11) and (12) regulate the activation of patient flow through main units. Constraints (11) ensures that a demand point is only served by a main unit if that main unit has capacity for at least one bed. Constraints (12) reinforces that beds can only be allocated if the main unit is open, using a Big-M formulation to deactivate capacity when it is not.

$$X_{dm} \leq P_m, \forall d \in D, \forall m \in M \quad (11)$$

$$P_m \leq BigM \times Z_m, \ \forall m \in M \quad (12)$$

Capacity Constraints

A. Main Unit Nurses' Workload

Each patient is visited twice a day by a nurse, usually one time in the morning and the other in the evening. Constraints (24) ensures that the total time required by nurses to visit all assigned patients does not exceed their available working time.

$$P_m \times 2 \times (t_{visit} + t_{travel}) \leq N_m \times H \times 60, \ \forall m \in M \quad (24)$$

Constraints (25) limits the number of nurses that can be assigned to each main unit to the existent number of nurses already allocated to the Home Hospitalization service of that facility. Unlike Constraints (17), there is no need to subtract one nurse for exclusive monitoring activities

$$N_m \leq \bar{N}_m, \ \forall m \in M \quad (25)$$

B. Doctors' Workload

Each patient is visited once a day by a doctor, usually in the morning. Constraints (26) ensures that the total time required by doctors to perform the required visits to their assigned patients does not exceed their available working time.

$$P_m \, (t_{visit} + t_{travel}) \leq D_m \times H \times 60, \ \forall m \in M \quad (26)$$

Constraints (19) limits the number of doctors that can be assigned to each main unit to the existent number of doctors already hired for the Home Hospitalization service of that facility.

$$D_m \leq \bar{D}_m, \ \forall m \in M \quad (19)$$

Appendix C – Set of Main Units

Information pertaining to the set of main units considered in the model including the name of the facility, ID and coordinates.

Table C: Set of Main Units.

Main Unit	ID	Latitude	Longitude
CUF Tejo	M1	38.7036	-9.1725
CUF Almada	M2	38.6661	-9.1977
CUF Descobertas	M3	38.7582	-9.0995
CUF Torres Vedras	M4	38.7582	-9.2586

Appendix D– Set of Demand Points

Information related to the set of demand points including the name of the facility, ID and coordinates.

Table D: Set of demand points.

Municipality	ID	Latitude	Longitude
Alcochete	D1	38.7776	-8.9625
Amadora	D2	38.7621	-9.2252
Cascais	D3	38.7170	-9.4355
Loures	D4	38.8358	-9.1663
Moita	D5	38.6727	-8.9889
Odivelas	D6	38.7981	-9.1822
Palmela	D7	38.5869	-8.8987
Sesimbra	D8	38.4547	-9.1035
Sintra	D9	38.8216	-9.3754
Almada	D10	38.6788	-9.1648
Barreiro	D11	38.6648	-9.0790
Lisboa	D12	38.7248	-9.1390
Mafra	D13	38.9617	-9.3318
Montijo	D14	38.7145	-8.9758
Oeiras	D15	38.7066	-9.3117
Seixal	D16	38.6456	-9.0985
Setúbal	D17	38.5448	-8.8900
Vila Franca de Xira	D18	38.9759	-8.9894

Appendix E – Set of Support Units

Information related to the set of support units including name of the facility, ID and coordinates.

Table E: Set of support units.

Support Unit	ID	Latitude	Longitude
Healthcare Centre CUF Almada	S1	38.6747	-9.1623
Healthcare Centre CUF Alvalade	S2	38.7527	-9.1433
Clinic CUF Alvalade	S3	38.7601	-9.1607
Healthcare Centre CUF Alverca	S4	38.9018	-9.0388
Healthcare Centre CUF Amadora	S5	38.7590	-9.2358
Clinic CUF Barreiro	S6	38.6620	-9.0790
Clinic CUF Belém	S7	38.6997	-9.1823
Healthcare Centre CUF Benfica	S8	38.7503	-9.2013
Healthcare Centre CUF Campo de Ourique	S9	38.7159	-9.1641
Hospital CUF Cascais	S10	38.7088	-9.4321
Healthcare Centre CUF Cova da Piedade	S11	38.6690	-9.1588
Healthcare Centre CUF Linda-a-Velha	S12	38.7150	-9.2410
Clinic CUF Mafra	S13	38.9450	-9.3546
Healthcare Centre CUF Massamá	S14	38.7530	-9.2859
Healthcare Centre CUF Mem Martins	S15	38.7965	-9.3445
Clinic CUF Miraflores	S16	38.7143	-9.2259
Clinic CUF Montijo	S17	38.7072	-8.9630
Clinic CUF Carcavelos	S18	38.6790	-9.3256
Healthcare Centre CUF Odivelas	S19	38.7926	-9.1735
Clinic CUF São Domingos de Rana	S20	38.7013	-9.3401
Hospital CUF Sintra	S21	38.7810	-9.3530
Healthcare Centre CUF Telheiras	S22	38.7679	-9.1730

Appendix F – Marginal Cost per Capacity Unit Increase

Table F presents the additional marginal cost per one unit increase in the capacity of the HH network.

Table F: Marginal Cost per Capacity Unit Increase.

Interval	ΔCost (€)	ΔCapacity
47-48	111 675.54	1.0
46-47	111 675.54	1.0
45-46	111 675.54	1.0
44-45	111 675.54	1.0
43-44	159 329.94	1.0
42-43	111 675.54	1.0
41-42	111 675.54	1.0

Interval	ΔCost (€)	ΔCapacity
40-41	111 675.54	1.0
39-40	111 675.54	1.0
38-39	159 329.94	1.0
37-38	111 675.54	1.0
36-37	180 295.54	1.0
35-36	111 675.54	1.0
34-35	111 675.54	1.0
33-34	111 675.54	1.0
32-33	111 675.54	1.0
31-32	159 329.94	1.0
30-31	111 675.54	1.0
29-30	111 675.54	1.0
28-29	111 675.54	1.0
27-28	111 675.54	1.0
26-27	159 329.94	1.0
25-26	111 675.54	1.0
24-25	180 295.54	1.0
23-24	111 675.54	1.0
22-23	111 675.54	1.0
21-22	111 675.54	1.0
20-21	111 675.54	1.0
19-20	159 329.94	1.0
18-19	111 675.54	1.0
17-18	111 675.54	1.0
16-17	111 675.54	1.0
15-16	111 675.54	1.0
14-15	159 329.94	1.0
13-14	111 675.54	1.0
12-13	180 295.54	1.0
11-12	111 675.54	1.0
10-11	111 675.54	1.0
9-10	111 675.54	1.0
8-9	111 675.54	1.0

Interval	ΔCost (€)	ΔCapacity
7-8	159 329.94	1.0
6-7	111 675.54	1.0
5-6	111 675.54	1.0
4-5	111 675.54	1.0
3-4	111 675.54	1.0
2-3	111 675.54	1.0
1-2	111 675.54	1.0
0-1	227 949.94	1.0

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