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Isabel da Luz Fonseca

ENHANCING HEALTHCARE EFFICIENCY

A STRATEGIC ANALYSIS OF HOSPITAL AT HOME AND ADDRESSING SCHEDULING AND ROUTING CHALLENGES IN A PORTUGUESE HEALTHCARE UNIT

Dissertação no âmbito do Mestrado em Engenharia e Gestão Industrial orientada pelo Professor Doutor Samuel de Oliveira Moniz e apresentada ao Departamento de Engenharia Mecânica da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

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Enhancing Healthcare efficiency

A strategic analysis of Hospital at Home and Addressing Scheduling and Routing challenges in a Portuguese Healthcare Unit

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“In all chaos there is a cosmos, in all disorder a secret order."

– Carl G. Jung, *The Archetypes and the Collective Unconscious* (1959)

Dedicado à avó Helena e avô Manuel que sempre sonharam estudar.

Agradecimentos

Agradeço, em primeiro lugar, à minha família por, não só me ter proporcionado esta oportunidade, como por, mesmo distante, ter sido força, motivação e apoio incondicional. Não existem palavras para descrever o quão importantes foram para este percurso e para a construção do meu caráter. Devo-vos tudo.

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Abstract

This dissertation aims to improve the efficiency of healthcare services under the Hospital at Home (HaH) initiative by exploring global best practices and addressing key challenges in scheduling and routing healthcare professionals. The central research problem focuses on optimizing the assignment of staff for home visits, taking into account constraints such as mandatory return times and individual patient needs. By analyzing the operational complexities of home healthcare, the study explores how optimization techniques can make services more efficient without increasing costs or requiring additional resources. The research adopts a heuristic-driven approach to solve the Home Health Care Scheduling and Routing Problem, enabling more efficient route planning and scheduling, thus minimizing travel times and balancing workloads across healthcare staff. As a result, the proposed solution has the potential to increase the patient capacity of the Home Healthcare Unit by 40%, a significant improvement that demonstrates the practical applicability of the approach. In addition, this dissertation conducts a thorough reviewof the global HaH model, examining its various implementations across different healthcare systems. This review includes an analysis of the model's impact on key stakeholders and explores the criteria for patient admission and exclusion. It highlights how these factors contribute to reducing hospital admissions and improving patient satisfaction. The findings suggest that expanding the HaH model, supported by an optimized scheduling and routing tool, could significantly enhance healthcare system efficiency by making better use of available resources, especially in response to an aging population and rising healthcare demands.

Keywords: Hospital at Home, Home Health, Efficiency, Admission criteria, Scheduling and Routing Problems, Heuristics.

Resumo

A presente dissertação tem como objetivo encontrar que fatores determinam a eficiência dos serviços de saúde no contexto da Hospitalização Domiciliária, explorando as melhores práticas e identificando os desafios do escalonamento dos profissionais de saúde neste contexto. O principal problema de investigação foca-se na otimização da alocação da equipa às visitas nas residências dos pacientes, considerando restrições como horário de retorno e necessidades dos pacientes. Ao investigar as complexidades operacionais dos cuidados de saúde domiciliares, o estudo examina como as técnicas de otimização podem simplificar os serviços sem aumentar custos ou exigir recursos adicionais. Uma abordagem heurística é adotada para resolver o Problema de escalonamento e roteamento dos cuidados de saúde domiciliares, permitindo um planeamento de rotas mais eficientes, minimizando assim os tempos de viagem e equilibrando as cargas de trabalho entre os profissionais de saúde. Esta abordagem permite aumentar a capacidade da Unidade de Hospitalização Domiciliária em 40%. Além disso, diferentes modelos de Hospitalização Domiciliária são investigados, demonstrando o seu impacto na redução das admissões hospitalares e na melhoria da satisfação dos pacientes. As conclusões sugerem que a expansão do modelo de Hospitalização Domiciliária, apoiado por uma ferramenta otimizada de escalonamento e roteamento, pode melhorar significativamente a eficiência do sistema de saúde ao fazer melhor uso dos recursos disponíveis, especialmente à luz do envelhecimento populacional e da crescente demanda por cuidados de saúde.

Palavras-chave Hospitalização Domiciliária, Eficiência na saúde, Critérios de admissão para HD, Otimização de problemas de escalonamento e roteamento, Heurísticas.

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ACRONYMS

HaH – Hospital at Home

OR – Operational Research

HHU – Home Hospitalization Unit

HBPC – Home-Based Primary Care

COPD – Chronic Obstructive Pulmonary Disease

ADL – Activities of Daily Living

HF – Heart Failure

GP – General Practitioners

ADL – Activities of daily living

HHCSRP – Home Health Care Scheduling and Routing Problem

MILP – Mixed Integer Linear Programming

CP – Constraint Programming

ALNS – Adaptative Large Neighbourhood Search

PSO – Particle Swarm Optimization

VRP – Vehicle Routing Problem

VRPTW – Vehicle Routing Problem with Time Windows

Np-hard – Non-deterministic polynomial time hard

1. INTRODUCTION

1.1. Contextualization and Motivation

The global population is aging, and this trend is particularly evident in Portugal, where individuals aged 65 and above made up 23.7% of the total population in 2023 (OECD, 2023). Projections suggest that this proportion will rise to 36.8% by 2080 (INE, 2020). Meeting the increasing demand for care services amidst a declining working-age population is a pressing concern in Portugal, and similar patterns are observed across Europe, although scarce exceptions. To address these challenges, marked by an increasing pressure within the healthcare system and advances in medical techniques and technologies, governments have been actively reforming healthcare systems to a more efficiency-oriented approach.

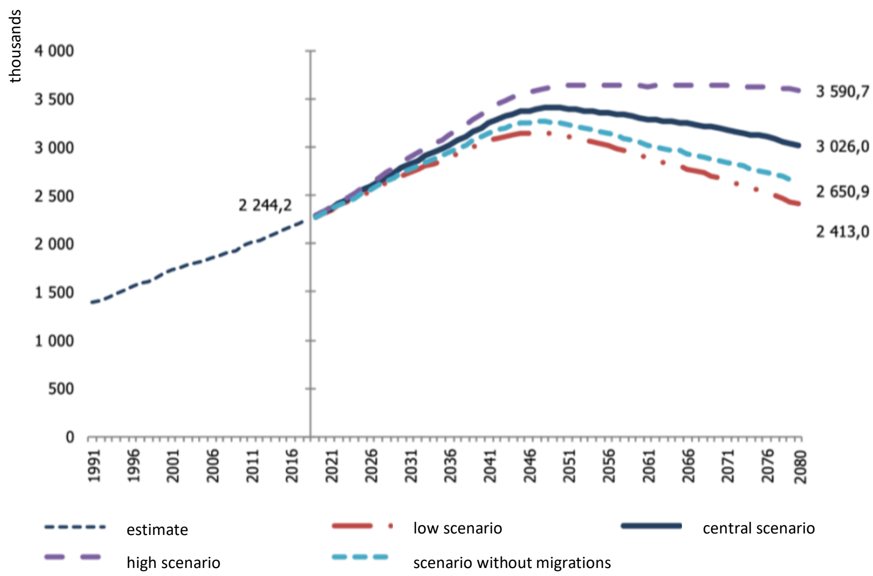


Figure 1.1 Estimates and projections for the population residing in Portugal aged 65 or over from 1991 to 2080. Source: INE (2020)

Hospital at Home (HaH) has become a popular way to treat patients in their homes who would otherwise require hospitalization in the traditional facilities, thereby alleviating bed pressure in hospitals, making them available for patients who cannot, for various reasons, receive this form of care at home and reduce costs, with evidences of success, particularly in terms of patient satisfaction and provision of quality medical services.

The latest *Plano de Emergência para a Saúde* (Ministério da Saúde, 2024) establishes strategic goals to improve efficiency in hospital services across Portugal, with one of the objectives being the expansion of HaH programs. The present work is expected to contribute with important insights to this initiative by identifying and addressing operational inefficiencies within HaH schemes.

To align with the Organisation for Economic Co-operation and Development recommendations for efficient spending (OCDE, 2023), an operational optimization tool tailored for the *Unidade Local de Saúde Almada-Seixal* was developed. This tool utilizes existing human resources, minimizing the need for further capital investments in staff and vehicles. Its primary goal is to streamline the scheduling process, reducing unnecessary time wastes with the planning process.

1.2. Objectives/Research Questions

Hospitals are highly complex systems, facing numerous challenges such as optimizing scheduling of staff and resources efficiently while balancing cost control and maintaining high-quality care. Addressing these challenges appropriately is essential for improving operational efficiency and ensuring patient satisfaction. The following research questions arise from these issues, aiming to explore how HaH programs and Operational Research (OR) techniques can contribute to solving these challenges:

- Why is HaH becoming increasingly popular?
- How does HaH impact hospital efficiency in terms of reducing inpatient occupancy, costs, and improving patient outcomes?
- What operational and logistical issues arise when organising HaH programs, and how can service operations management and OR mitigate these issues?
- How can a customized scheduling and routing optimization system be developed for the HaH program of the *Unidade Local de Saúde Almada-Seixal*?
- What are the measurable benefits of implementing an optimized scheduling and routing system at the HaH program of the *Unidade Local de Saúde Almada-Seixal*?

1.3. Structure

The structure of this dissertation is divided into seven main chapters. Collectively, these chapters provide a strategic and comprehensive analysis of the Hospital at Home (HaH) model, while also addressing the scheduling and routing challenges faced by the Hospital at Home Unit (HHU) within the *Unidade Local de Saúde Almada-Seixal*.

Hence, the current chapter introduces the key topics and objectives that will be disclosed throughout the dissertation. Chapter 2 examines the background in which HaH rose to prominence and became an integral component of modern healthcare delivery systems. Moreover, it covers the concept of HaH, its impact on communities—particularly on stakeholders—its organizational structure, and reviews relevant literature on scheduling and routing problems in the context of home healthcare. Chapter 3 provides a detailed description of the operational system currently in place at *Unidade Local de Saúde Almada-Seixal*. In chapter 4, the methodological approach and development process used to address the scheduling and routing problem are explained. Chapter 5 presents the results of the optimization solution, analysing its effectiveness and performance. Chapter 6 focuses on the practical implications of the developed system for visit scheduling and staff routing, and proposes improvements and future for research directions. Finally, chapter 7 concludes the work by summarizing the key findings and presenting final remarks.

2. LITERATURE REVIEW

This review aims to trace the evolution of the HaH model globally and examine the factors behind its increasing interest. Additionally, it analyses the impact of HaH on its stakeholders to identify practices that can lead to a positive effect both for them and healthcare organizations. The review also compares various home care programs with HaH to determine the most appropriate admission criteria and service delivery methods that can positively impact healthcare organizations and enhance efficiency.

Furthermore, key literature on Scheduling and Routing Problems in home healthcare services is examined, focusing on the essential parameters and considerations specific to these issues. Gaining a comprehensive understanding of the HaH program, alongside the theoretical foundations of Scheduling and Routing Problems, is vital to effectively support the expansion of HaH practices in Portugal and to improve operational efficiency in the healthcare sector.

2.1. Historical contextualization of Hospital at Home

Hospitals offer vital resources for the treatment of acute illnesses, yet hospitalizations can pose significant risks, especially for individuals with a more fragile or declining immune system, such as the elderly population, who may even experience delirium, post hospitalization syndrome, hospital-acquired infections, and functional decline (Truong & Siu, 2024). Besides, external factors such as overcrowding of hospitals and emergency departments; the emergence of advanced telehealth technologies that allow clinicians to remotely observe patients, conduct examinations, and exchange information; the growing demand for improved care experiences among consumers; and the pressure from payers to develop cost-effective, high-quality care demand for alternative approaches to the traditional acute care provided in hospitals (Leff, 2009).

Historically, HaH emerged in 1947 in the USA, after the Second World War, precisely due to the urgent need to decongest hospitals and promote patient-centred treatment. Dr. Bluestone, a pioneer in this field, pointed out that home care is essentially an extension of the hospital into the home. Cherkasky (1949) goes further and defends that HaH is "definitely better" than the usual hospitalization, for suitable patients. This model of care has rapidly gained notoriety and expanded through North America and Europe.

The first mention of such a HaH program in Europe dates back to 1951 in France (Cotta et al., 2001). Later, in 1961, *Santé Service Bayonne* was originally founded to enable terminally ill cancer patients to die at home and was then extended to the elderly and physically disabled. In 1981, 1520 adults (mostly over 65 years old) were treated at home under two different approaches, which differed in the intensity of care and the number of visits required (Morris, 1983). This program continues to run today and serves as an inspiration for other countries that joined the program, especially in the 1970s and the 1980s (Cotta et al., 2001), such as the United Kingdom (Mowat & Morgan, 1982).

HaH in Spain was legally recognised in 1986 but lacked specific regulations and incentives to promote its expansion. Despite irregularities in its development, HaH emerged in 2006 as a recognised aid modality in the portfolio of the Spanish National Health Service (Estrada Cuxart et al., 2017). The Spanish HaH model of care served as an inspiration for the Portuguese.

Countries around the world faced various challenges, progress, and setbacks in scaling up HaH, which depended on the individual initiative of health professionals and managers. It was not until 1996 that the World Health Organization (WHO) Regional Committee for Europe committed to promoting, standardising, and more adequately documenting this form of care (Delerue & Correia, 2018). In the United States, HaH became an alternative to the traditional hospital model in 1991, following the publication of legislative decrees. In Europe, it took a little longer, as it was not until the late 2000s that HaH became a complete alternative to traditional hospitalization, with Home Hospitalization Units (HHU) having the status of a separate hospital or being integrated into a hospital department. These can be public, private, for-profit, or non-profit (Rossinot et al., 2019). However, during the COVID-19 pandemic, HaH experienced divergent effects: many saw this as an opportunity to establish these programs (Gómez-Centurión et al., 2022; Sitammagari et al., 2021); however, some already in practice saw their focus and human resources being reallocated to other areas (Truong & Siu, 2024). In any case, it is indisputable that the latest pandemic and developments in remote monitoring technology pressured health systems to adopt new strategies, and HaH is a great solution (Edgar et al., 2024).

Currently, HHUs are configured as units for healthcare, teaching, and performing clinical research (Delerue & Correia, 2018).

In Portugal, the first HHU was set up at *Hospital Garcia de Orta* in 2015. Prior to this, the few resources available at home were dedicated to palliative care. At that time, there were 11 home care centres nationwide (Alves, 2016). Its implementation took place in the context of an increasing prevalence of chronic diseases and an aging population, resulting in increasing pressure on the number of available hospital beds (Chan, 2022). Furthermore, the healthcare sector has faced and continues to face a scarcity of human resources due to low salary offers and the exhaustion of professionals, with nurses being particularly affected, as some may abandon their professional careers, while others leave the country or switch from the national health service to the private sector (Caetano, 2021). This situation is particularly concerning for HaH services, where nurses are the primary human resources responsible for providing care. In addition, global trends such as the ageing population, the increase in chronic morbidity, the low number of available beds in inpatient wards and the high mortality rate due to infections in intensive care result are leading to rising expenditure on public health and long-term care, which is estimated to increase by 3% of the GDP by 2040 (OCDE, 2023), doubling the need to implement innovative alternatives to conventional treatments and make efficient use of available resources.

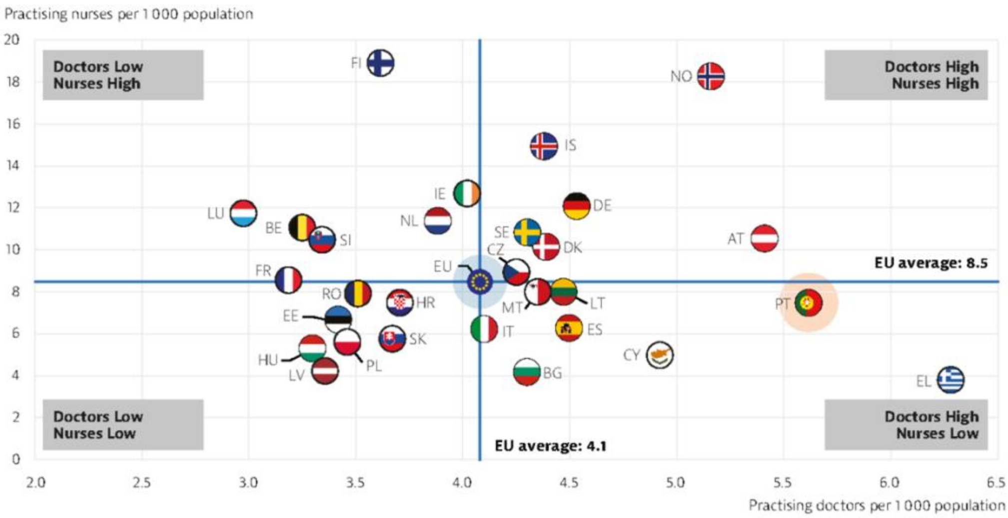


Figure 2.1 Active health professionals in Portugal and Europe. Source: OECD (2023).

In 2018, the legal framework (Despacho n.º 9323-A/2018, 2018) was created as a strategy for implementing HHU in the Portuguese National Health Service known as *Serviço*

Nacional de Saúde (SNS). Still, in the same year, the Portuguese General Directorate of Health (DGS) published a Clinical Guidance Standard regarding the organizational quality of home hospitalization in adulthood (Norma No. 020/2018, 2018). The legislation implementation encouraged the establishment of 23 additional HHUs, which committed to having HaH up and running by the end of 2019 (SNS, 2018). This number has increased unexpectedly, and by the end of 2022, 36 health facilities were operating HaH programs geographically distributed across the five regions of the country, with a total of 339 beds, which is equivalent to the capacity of a medium-sized hospital (Pizarro, 2023).

2.2. Concept of Hospital at Home

HaH systems differ in their philosophy and focus of care according to the orientation and general organizational guidelines of each country's healthcare system in terms of the source of funding and the profile of healthcare providers. There is not even a consensus on how to call it. Terms in use vary from "Hospital In The Home" (more common in Australia), "Home Hospital" (more common in the UK), "Home Hospitalization" (more common in Europe) and similar terms. In this dissertation, "Hospital at Home" will be the term used, as referred to in most of the literature, which is the most common term in the United States where the concept was born.

In general, the literature on this topic indicates that most countries follow the French model, which provides personal, nurse-led care services and promotes two known modalities of home health services in parallel: HaH and home-based primary care (HBPC). HaH differs from Home-Based Primary Care (HBPC) as it focuses on acute, short-term care that would otherwise require hospitalization, while HBPC generally serves long-term chronic care needs. While most countries distinguish between HaH and HBPC, Germany and the United States often integrate the two, leading to potential misconceptions. Although HaH was created to prevent nosocomial infections and is mainly intended for older people, age is no longer a limiting factor (Cotta et al., 2001).

Leff and Montalto (2004) point out that the HaH definition should emphasise the motivation of the model, which turns out to be contentious as it varies from country to country and even within countries depending on hospital management, resources and scope of medical specialities. To find a resolution, we should focus on the touchpoints which encompass reducing nosocomial and iatrogenic complications, honouring patients' wishes for care, and reducing costs.

Firstly, it is crucial to correctly assess the patient's state of health to ensure that it is acute and that the HaH is of limited duration. The reason for discharge can be improvement or cure, death, stabilisation of the pathological process, readmission to the hospital, or referral to primary care. Cotta et al., (2001) point out that if the temporary nature of HaH is not taken into account or its function is inadequately interpreted, there is a risk of duplication of treatment, as chronic monitoring and home monitoring should be the responsibility of primary health care services, with adequate clinically deliberated exceptions.

Secondly, to ensure optimal care, HaH programmes must offer the full hospital substitution, with the hospital bearing responsibility for providing the intensity of care appropriate to the severity of the illness treated, including medical and nursing care, medication, equipment, and, if needed, occupational therapy, physical therapy, transportation or even housekeeping, basically everything that would otherwise be provided in the hospital. Without such care, patients may still be at risk of comorbidities or exacerbations in their health. Moreover, their overall experience could be unsatisfactory, leading to psychological distress and a potentially heavier economic burden (Cherkasky, 1949; Cotta et al., 2001; Leff & Montalto, 2004).

Thirdly, HaH must be subject to regulatory and governance obligations.

The Portuguese standard (Norma No. 020/2018, 2018) is based on the definition by Cotta et al. (2001) and Leff and Montalto (2004). However, it is too broad, and it is difficult to distinguish between HBPC and HaH:

> *"Hospital at Home (HaH): is an alternative to conventional hospitalization, which provides clinical assistance in a continuous and coordinated manner to those patients who require hospital admission, also fulfilling a series of clinical, social and geographic criteria that allow hospitalization at home under the supervision of the HD always according to the wishes of the patient and their family;"*

On the other hand, the complicated scenario and the pressures under which the SNS finds itself may be the reason why the description is not precise. However, HaH and HBPC should be incentivised separately to prevent unnecessary risks, as highlighted by Cotta et al. (2001).

In sum, I believe an accurate conceptualization of HaH should be: seamless, round-the-clock, hospital-level care in the patient's environment as a full substitute for acute clinical care provided to those who, even though not need the entire hospital infrastructure for their treatment, require care that exceeds in complexity the one provided by primary healthcare. Patients admitted must fulfil a range of clinical, social, and geographical conditions, with their consent and that of their family. Consequently, staff, equipment, technologies, medicines, and skills follow the patient home in adjusted regularity to provide coordinated care, working with patients and carers under the full responsibility of the HHU.

2.3. Impact on Stakeholders

Although many authors assert that HaH is safe, effective and able to respond to a multitude of acute medical conditions while endeavouring a patient-centred approach to treat each patient with dignity and in optimal environment, with benefits for both the patient's family and the hospital (Leong et al., 2021), it is crucial to substantiate these claims with empirical evidence. To this end, experimental studies, such as randomized controlled trials (RCT) and quasi-experimental studies were conducted to provide robust support (Popenoe et al., 2021). Three systematic quantitative reviews were analysed, incorporating a total of 40 studies from 8 different countries (Figure 2.2), with the aim of uncovering the impact of HaH on stakeholders in various dimensions.

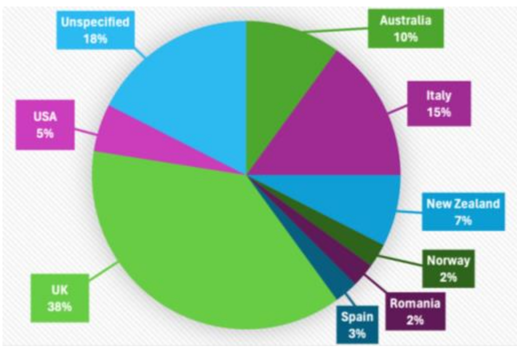


Figure 2.2 Distribution of clinical trials analysed by country of origin.

2.3.1. Impact on Patients

Patients are the principal target population of HaH, therefore the most impacted.

2.3.1.1. Mortality

The available data from multiple trials indicates that early-discharged patients do not experience a statistically significant difference in mortality rates. While the data for patients recovering from chronic obstructive pulmonary disease (COPD), a stroke or a hip replacement surgery suggests a potential reduction in mortality with moderate certainty for the first two groups and low certainty for the last one, the evidence for patients recovering from elective surgery is limited due to a small sample size. On the other hand, although there is no significant evidence, this analysis found HaH to have the probabilistic potential to somewhat harm the longevity of the elderly diseased, however, most recent analyses can't find this evidence (Gonçalves-Bradley et al., 2017; Shepperd & Iliffe, 2005a).

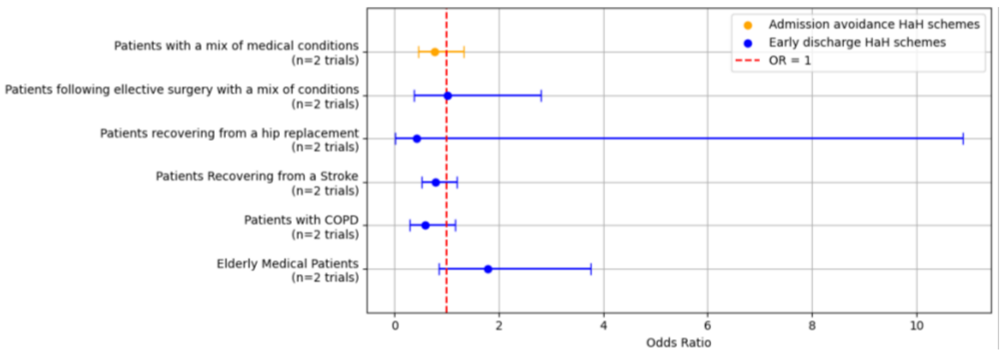


Figure 2.3 Mortality comparison between HaH and hospital. Adapted from: Shepperd & Iliffe (2005)

Edgar et al. (2024) delved deeper into the impact of admission avoidance in HaH schemes as they combined different RCTs assessing various medical conditions. Findings were in line with the ones by Shepperd & Iliffe (2005): no significant impact on mortality rates at both three- and six-months follow-up.

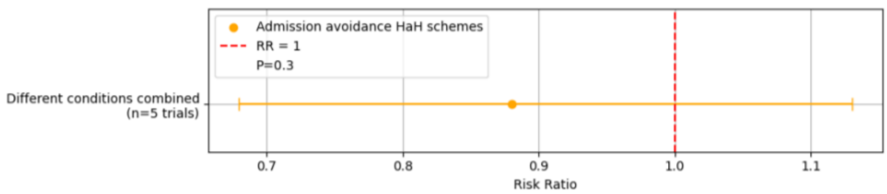


Figure 2.4 Mortality comparison between admission avoidance HaH and hospital at 6 months follow-up. Adapted from: Edgar et al. (2024).

Another meta-analysis was made around admission avoidance through the provision of hospital care at home, but this time using Hazard Ratio to measure changes in mortality rates. During the first three months, mortality in the HaH group was either the same or lower compared to patients treated in a hospital setting, though not significantly. After six months, mortality was notably lower for patients who avoided hospital admission and received care at home (Figure 2.5). Nonetheless, Shepperd et al. (2009) caution that this finding is not definitive, citing a trial involving stroke survivors where, at the three-month mark, mortality was significantly lower in patients treated in hospital stroke units compared to those receiving HaH care.

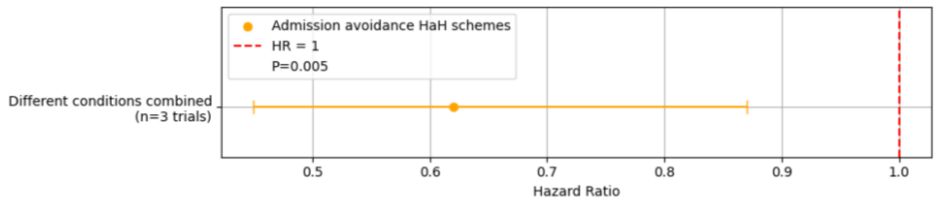


Figure 2.5 Mortality comparison between admission avoidance HaH and hospital at 6 months follow up. Adapted from: Shepperd et al. (2009)

2.3.1.2. Readmission to Hospital

Regarding hospital readmission rates, no significant differences were observed between patients receiving early discharge care and those under standard care. Yet, early discharge HaH was deemed unsuitable for elderly patients recovering from knee replacement surgery, as one trial reported that 30% of them were re-admitted to the hospital, although no statistical difference in readmission rates between the two care models was confirmed (Figure 2.6; Shepperd & Iliffe, 2005). For patients with COPD, the odds of readmission within three months were lower for those treated under HaH care, with moderate certainty. In contrast, for stroke patients, no difference in readmission reduction was found between the HaH and control groups, with greater uncertainty compared to COPD patients (Figure 2.7; Shepperd & Iliffe, 2005).

Elective surgery outcomes found no significant evidence of hospital readmission in one trial, but there was a decreasing effect in hysterectomies and the opposite in knee and hip replacement surgeries, with high levels of uncertainty. One trial investigating both surgical and medical patients together at the three-month follow-up, found that admission to the hospital after discharge was 1.34 times more likely to occur for patients treated in the HaH group, with moderate certainty, particularly for those who had not been previously hospitalized (Figure 2.7; Shepperd & Iliffe, 2005).

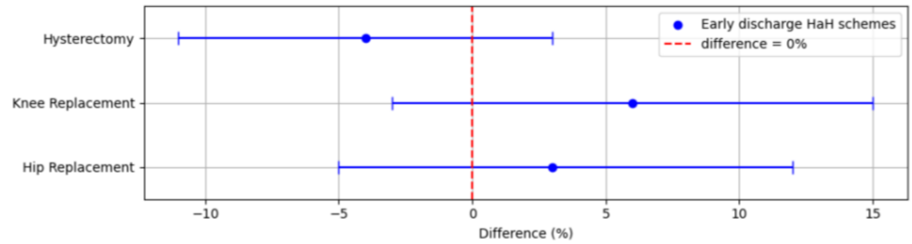


Figure 2.6 Readmission to hospital after discharge comparison between patients following different types of surgeries. Adapted from Shepperd & Iliffe (2005).

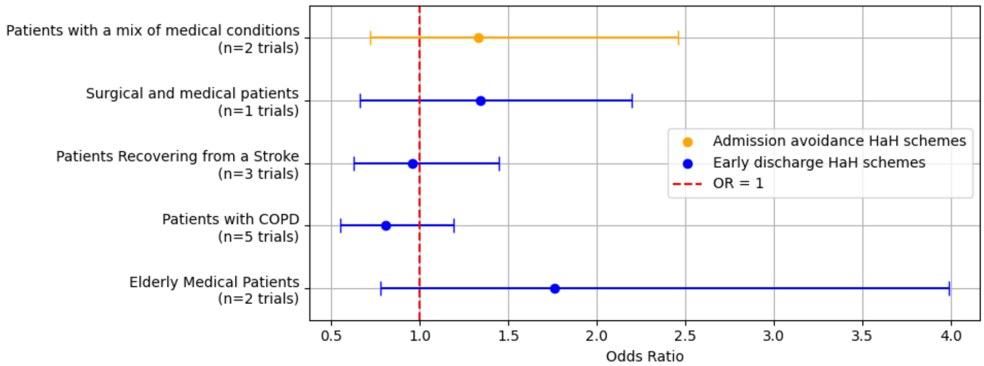


Figure 2.7 Readmission to hospital comparison between patients with different medical conditions and HaH schemes. Adapted from Shepperd & Iliffe (2005).

In Edgar et al.'s (2024) research, outcomes indicated that admission avoidance HaH probably has none to slightly increased effect on hospital readmissions, with a moderate level of certainty. Heterogeneity among the trials included tendency to favour the lack of risk of higher readmission between groups (Figure 2.8). The Shepperd et al.'s (2009) research failed to find significant results and fell into a wide confidence interval that favoured inpatient care but with low levels of certainty.

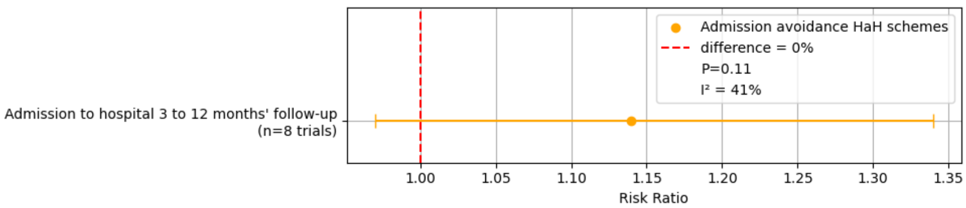


Figure 2.8 Risk ratio comparison of hospital readmissions between admission avoidance HaH and conventional Hospital over a 3 to 12 months follow-up period. Adapted from: Edgar et al. (2024).

2.3.1.3. Clinical Outcomes

Shepperd & Iliffe (2005) gathered data from a trial recruiting elderly COPD patients, finding that 18% more patients in the early discharge group were prescribed antibiotics compared to those in hospital care. However, no differences were noted in forced expiratory volume. In another trial on varicose vein surgery, HaH patients experienced significantly more major and minor complications. Despite this, fewer HaH patients across mixed conditions experienced short-term confusion during care. When analysing all complications in admission avoidance schemes, no significant differences were found between HaH and hospital care. Results are displayed in Figure 2.9.

Edgar et al. (2024) and Shepperd et al. (2009), when analysing admission avoidance HaH, reported fewer bowel or urinary complications (Figure 2.9) and a lower risk of delirium (measured by the Confusion Assessment Method) in HaH patients (Figure 2.10; Edgar et al., 2024). Their findings also converged on a trial involving dementia participants, where, HaH care led to significantly fewer prescriptions of antipsychotic drugs at discharge (Figure 2.9). This particularly vulnerable group of patients supports the evidence that HaH may reduce the risk of cognitive decline (H. Chen et al., 2024).

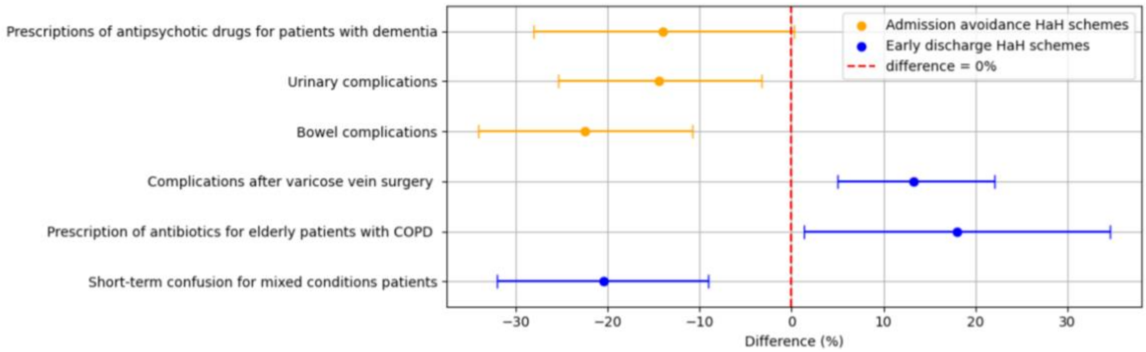


Figure 2.9 Percentage Difference in clinical outcomes between distinctive HaH Schemes for various patient conditions. Adapted from: Edgar et al. (2024) and Shepperd et al. (2009)

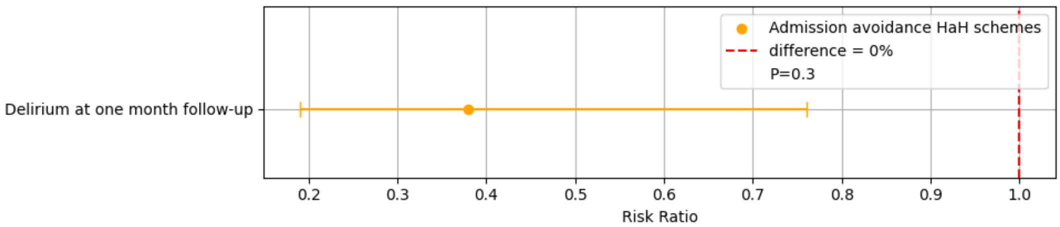


Figure 2.10 Risk ratio of delirium comparison between admission avoidance HaH and conventional Hospital at one-month follow-up. Adapted from: Edgar et al. (2024)

2.3.1.4. Satisfaction

Trials involving stroke patients over 65 years old, assessed different results. While some report significantly higher levels of satisfaction with care (Figure 2.11), others reject a statistically significant difference. One particular trial examined different aspects of satisfaction but only revealed a greater level of satisfaction regarding participation in the treatment process. For the same age range, it appears that individuals with COPD prefer to receive treatment at home (Figure 2.11; Shepperd & Iliffe, 2005).

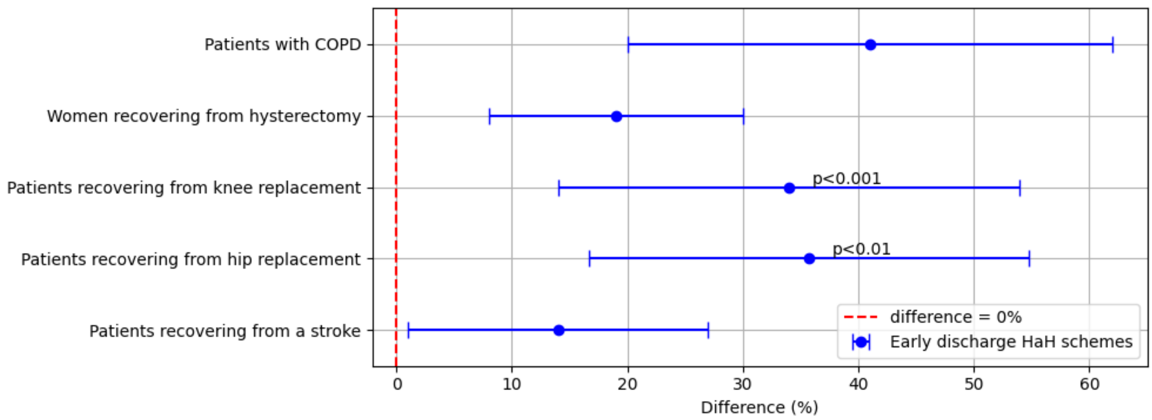


Figure 2.11 Comparison for preferred place of care between home and hospital. All data collected by: Shepperd et al. (1998).

Patients recovering from elective surgery fall into harmony regarding no differences in satisfaction with care between HaH early discharge and common hospitalization. Nevertheless, home is their preferred place of recovery (Figure 2.11). When asked about the advantages and disadvantages of their care they highlight more benefits for themselves but feel their caregivers are at a disadvantage (Figure 2.12). Additionally, HaH schemes seem to enhance communication, contributing to stronger relationships (Shepperd & Iliffe, 2005a).

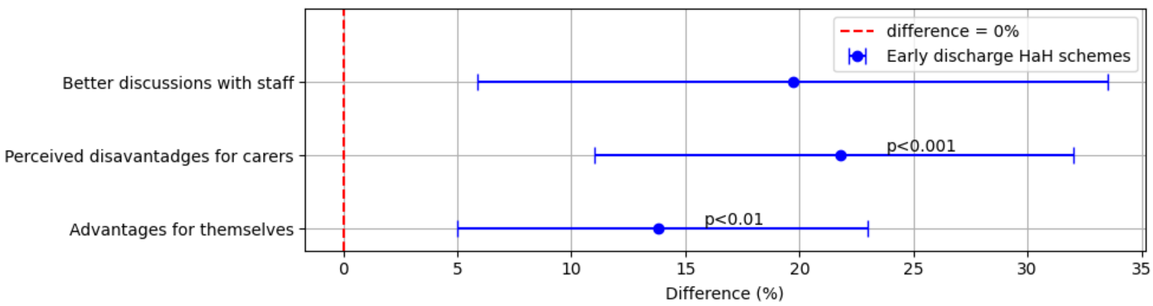


Figure 2.12 General perceptions by patients treated in HaH. Adapted from: Shepperd & Iliffe, (2005).

On the other hand, women recovering from a hysterectomy reported resuming parental responsibilities before being fully recovered (Figure 2.13; Shepperd & Iliffe, 2005a).

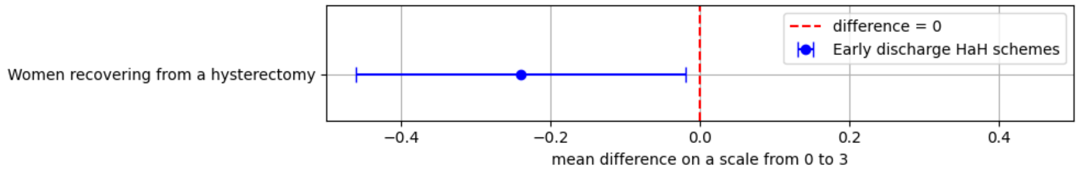


Figure 2.13 Resume of parental responsabilities before recovery. Adapted from: Shepperd & Iliffe (2005).

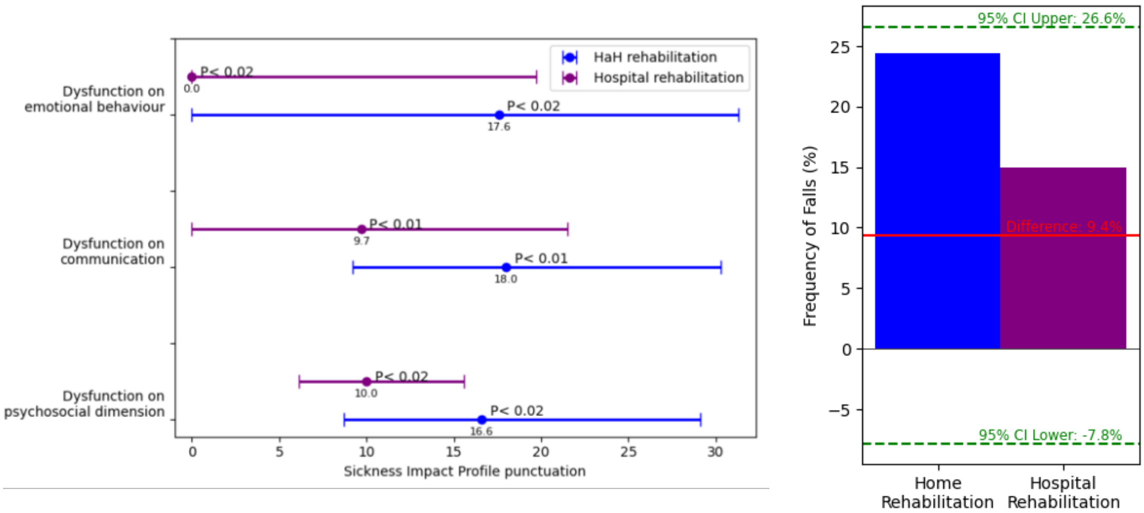
For terminally ill patients, satisfaction was reportedly higher in those treated at home after one month (P = 0.02), although this difference diminished as sample sizes reduced over time (Shepperd & Iliffe, 2005a). In trials involving mainly older patients with various conditions, those in admission avoidance HaH schemes showed significantly higher satisfaction than hospital-treated patients. One trial found a 0.9-point difference on a four-point scale (P < 0.001) favoring the HaH group, while another showed a 3-point difference on an eighteen-point scale (P < 0.001) (Edgar et al., 2024; Shepperd et al., 2009; Shepperd & Iliffe, 2005a).

A recent analysis revealed that 27% more patients with cellulitis (P < 0.001) and 40% more with community-acquired pneumonia (P < 0.001) in HaH care expressed higher satisfaction with their care location, though response rates differed. Among COPD patients, 94% rated HaH care as "very good" or "excellent," compared to 88% in the hospital group (P = 0.83). Several other trials also favored HaH in overall satisfaction scores, while some showed similar high satisfaction across both groups, though one point lower for hospital care (Edgar et al., 2024; Shepperd et al., 2009).

While HaH appears to boost satisfaction with care (low-certainty evidence), not all patients or caregivers fully accept this model, which may influence outcomes due to the active role participants play in choosing their care setting (Edgar et al., 2024; Shepperd et al., 2009).

2.3.1.5. Assessed outcomes

Shepperd & Iliffe (2005) analysed eight trials, finding no significant differences between early discharge and standard care for most dimensions. However, in one trial involving stroke patients, patients reported increased dysfunction in psychosocial dimensions, communication, and emotional behavior in the early discharge group compared to routine rehabilitation, though these differences were only observed at the three-month follow-up (Figure 2.14(a)). Additionally, although confidence intervals did not exclude the null, a higher frequency of falls was reported in home care (Figure 2.14(b); Holmqvist et al., 1998). Another trial using the Geriatric Depression Scale found that stroke patients receiving HaH care showed a significant improvement, with a median difference of 7 points on a 0-30 scale (P < 0.001) (Shepperd et al., 2009).



(a) (b)

Figure 2.14 (a) Functional and well-being status comparison between hospital and home; **(b)** Frequency of Falls in Home Rehabilitation vs routine rehabilitation. Adapted from: Holmqvist et. al (1998).

A trial involving stroke patients found that those receiving early discharge were more likely to be independent in activities of daily living (ADL) at 26 weeks follow-up (Figure 2.15). HaH interventions appeared especially beneficial for patients with moderate to severe strokes, improving global independence and daily functioning, as indicated by subgroup analysis (Figure 2.16). This may be due to the more intensive and personalized care that can be effectively delivered in a home setting (Shepperd & Iliffe, 2005a).

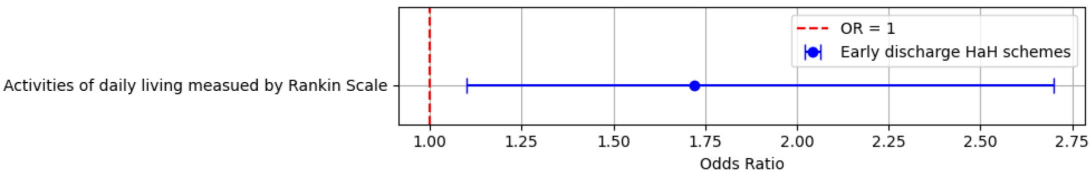


Figure 2.15 Independence in activities of daily living at 26 weeks follow-up. Adapted from: Indredavik et al. (2000)

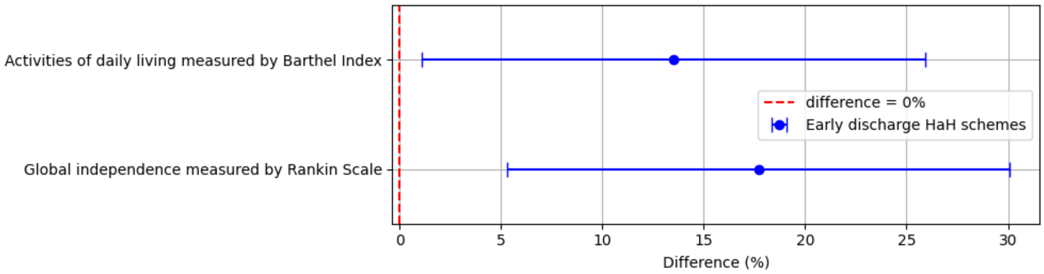


Figure 2.16 Subgroup analysis results for stroke patients, excluding mild cases. Adapted from: Indredavik et al. (2000).

Two trials evaluating elective surgery found no significant differences between patients who underwent early discharge to HaH care and those who completed full recovery in the hospital. A separate trial using the Dartmouth COOP charts showed that HaH positively impacted patients' quality of life (Figure 2.17). Additionally, patients recovering from a fractured neck of femur showed significant improvement on the Modified Barthel Index at four months, with a median difference of three points, though no confidence interval was reported. Functional status and psychological well-being remained similar in both groups (Shepperd & Iliffe, 2005a).

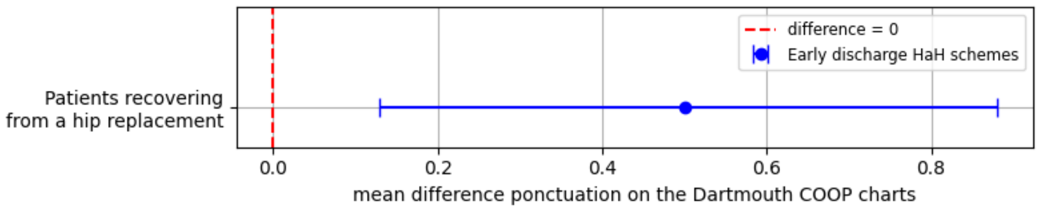


Figure 2.17 Mean difference in quality of life scores for patients recovering from a hip replacement, measured using the Dartmouth COOP charts. Adapted from: (Shepperd & Iliffe, 2005a).

For terminally ill patients, no statistically significant differences were detected in functional status, psychological well-being, or cognitive status between those receiving HaH and those receiving in-patient care. Since patient-reported outcomes showed no clear differences, one trial assessed outcomes from the perspective of healthcare professionals and caregivers. It found that HaH care might not be the optimal arrangement for psychological well-being (Figure 2.18). However, the results varied by assessor, highlighting the fragility of the evidence. No significant differences were found in other domains (Shepperd & Iliffe, 2005a).

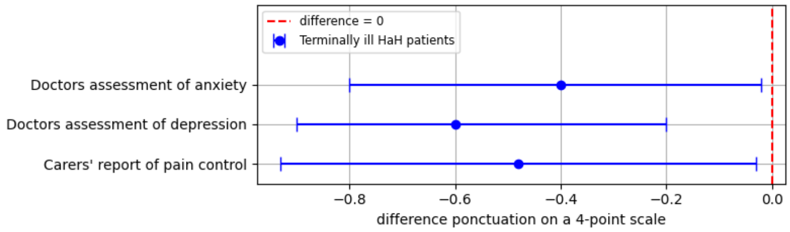


Figure 2.18 Difference in assessments for terminally ill patients receiving Hospital at Home (HaH) care compared to in-patient care, using a 4-point scale. Adapted from: (Shepperd & Iliffe, 2005a).

In a study involving cancer patients, quality of life changes were assessed before and after a febrile neutropenia episode. Regarding role function, a measure of involvement in social life, hospital patients scored 0.2 points higher on a 0 to 100 scale compared to HaH participants, with statistical significance ($P = 0.05$). However, emotional function results showed a mood disorder in hospital patients, while HaH participants demonstrated positive emotional behaviour ($T = 3.27$, $C = -6.94$, $P = 0.04$) (Edgar et al., 2024).

For patients with dementia, HaH care led to significant improvements: sleep quality improved by 34 percentage points ($P < 0.001$), agitation and aggression decreased by 32.5 percentage points ($P < 0.001$), and 31.0% fewer patients experienced feeding problems ($P < 0.001$) after hospital discharge (Edgar et al., 2024; Shepperd et al., 2009).

Patients with cellulitis and those with decompensated heart failure (HF) were assessed using the SF-36 survey. For cellulitis patients, comparisons between day 0 and day 6 showed declines in physical functioning for HaH patients compared to hospital care, as seen in Figure 2.19 (H. Chen et al., 2024). In HF patients, Mendoza et al. (2009) reported moderate evidence favoring HaH for physical and mental health outcomes over 12 months, although these results were not statistically significant. For cellulitis patients, the short six-day follow-up revealed mixed results: physical health deteriorated, but patients reported experiencing less pain.

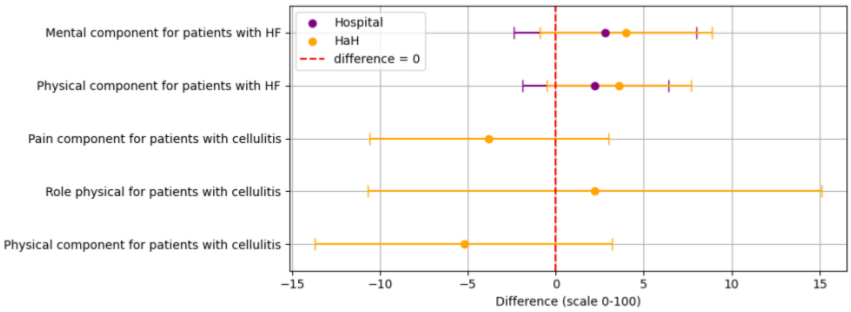


Figure 2.19 Difference in quality of life outcomes for patients across various conditions comparing HaH care with hospital-based recovery. Adapted from: H. Chen et al. (2024).

Quality of life of elderly patients with acute decompensation of chronic HF and exacerbations of COPD was assessed using the Nottingham Health Profile, which measures perceived emotional, social, and physical health issues. HaH obtained better mean scores in both trials than brick-and-mortar hospitalization. However, the wide standard deviations, especially in COPD patients, included negative values, indicating a high level of uncertainty despite the low probability of rejecting significant differences between the groups.

For psychological health, COPD patients receiving HaH care had significantly lower Geriatric Depression Scale scores at six months (T: −3.1, SD 4.7; C: 0.7, SD 3.2; P < 0.001), indicating better outcomes. HF patients also showed worse psychological outcomes under HaH care compared to hospital care, but results were reported as mean changes (T: 1.48, SD 1.86; C: 0.12, SD 3.36; P = 0.02). Overall, the evidence suggests moderate certainty (Edgar et al., 2024).

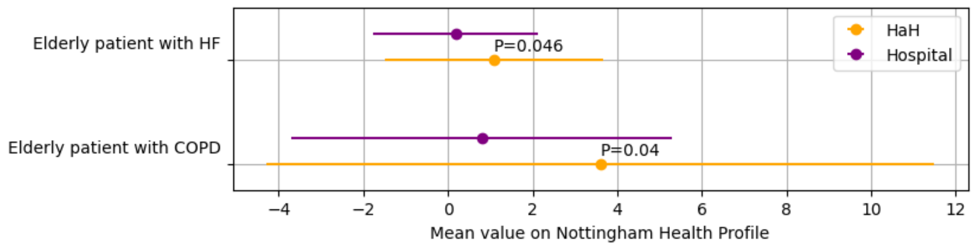


Figure 2.20 Comparison of mean values between HaH and hospital care for elderly patients with HF and COPD, based on the Nottingham Health Profile. Adapted from: (Edgar et al., 2024)

In terms of functional ability, most trials evaluating the effectiveness of admission avoidance found no significant differences compared to hospital care. Nevertheless, a few exceptions reported significance (Edgar et al., 2024; Shepperd et al., 2009). For example, Shepperd et al. (2009) highlighted a study showing that HaH patients demonstrated better independent living skills (mean difference 0.57, P = 0.04), although the difficulty of measuring these skills in a hospital setting makes the real impact unclear.

Another study, documented by Edgar et al. (2024), reported a significant improvement in instrumental activities of daily living (IADL) — such as cooking, cleaning, and managing finances — between admission and discharge for HaH patients, particularly among elderly individuals with acute medical conditions. HaH patients showed a positive change, while hospital patients did not (Guo & Sapra, 2024).

No significant statistical deviations were found in any other study. Even so, one trial caught my eye: 5% more hospital-based patients had worsened IADL skills from admission to discharge, but 30 days post-discharge, 3% more HaH patients showed deterioration in IADL abilities. For ADL, such as self-care and mobility (Edemekong et al., 2024), no significant differences were observed between the groups from admission to discharge. However, 30 days later, 5% more hospital patients exhibited poorer ADL performance compared to those in HaH. No additional statistical data or sample size details were provided for this trial (Edgar et al., 2024).

2.3.1.6. Place of Residence following Discharge

The place of residence following discharge was assessed to evaluate elderly patients' ability to live independently. Shepperd & Iliffe (2005) research indicated that patients in the early discharge group may have reduced likelihood of transfer to a care home after an acute episode compared to those receiving standard care. However, this difference diminishes over time, specifically by 12 weeks and one year after discharge. Even so, 18.6% more patients remained in their homes after one year. Stroke patients recovering at home also showed a reduced tendency to be transferred to nursing homes by six weeks post-discharge, though this was not statistically significant. Results are presented in Figure 2.21.

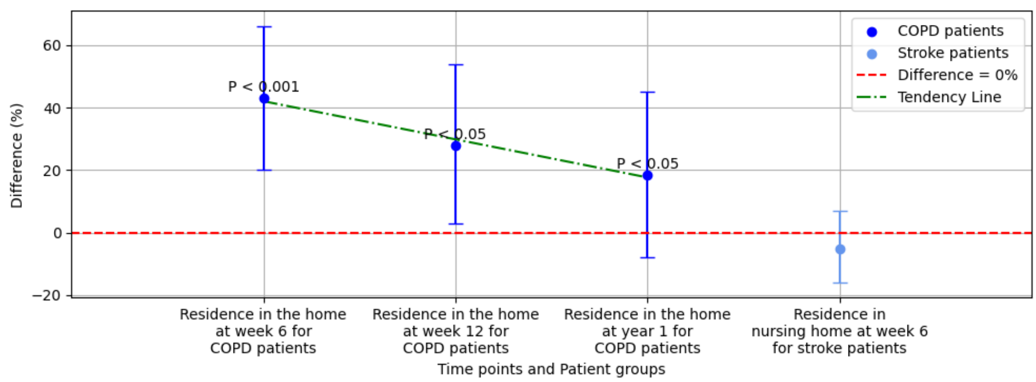


Figure 2.21 Place of residence following discharge for stroke and COPD patients, comparing early discharge (Hospital at Home, HaH) with standard care. Adapted from: Shepperd & Iliffe (2005).

The collection of trials by Shepperd et al. (2009) supported the finding that fewer patients in the HaH group were living in institutional settings at follow-up. Figure 2.22 presents the results from three different trials, including one trial with elderly dementia patients and two with seniors recovering from strokes. Additionally, Edgar et al. (2024) calculated the risk ratios from four separate trials, which are also shown in Figure 2.22.

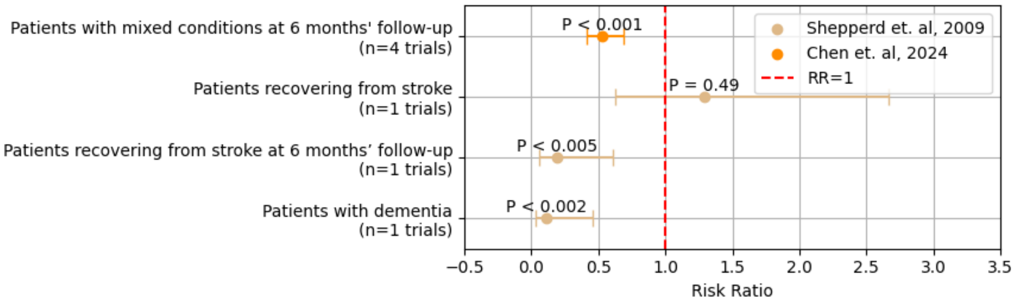


Figure 2.22 Risk ratios of patients living in institutional settings at various follow-up times, comparing HaH with hospital care. Adapted from: Shepperd et al. (2009) and Edgar et al. (2024).

2.3.2. Informal Carer

Three trials measured elderly carer burden using various metrics, but none detected a significant difference between carers whose relatives were treated at home and those visiting relatives in the hospital. Satisfaction was also evaluated, with only one trial showing a greater preference for HaH (Figure 2.23; Shepperd & Iliffe, 2005).

A trial from 1978, recruited carers of post-surgery patients and reported lower satisfaction with the length of hospital stay, although no statistical results were provided. In another trial from the same year and type of participants, carers viewed HaH care as advantageous for others involved in the care process but not for themselves or the patients, compared to hospital-based recovery. Conversely, Shepperd et al. (1998) found that most carers of women recovering from hysterectomy preferred HaH care, though 27% did not. Two other trials failed to detect differences in satisfaction between groups, and another found no changes in carer burden (Shepperd & Iliffe, 2005a).

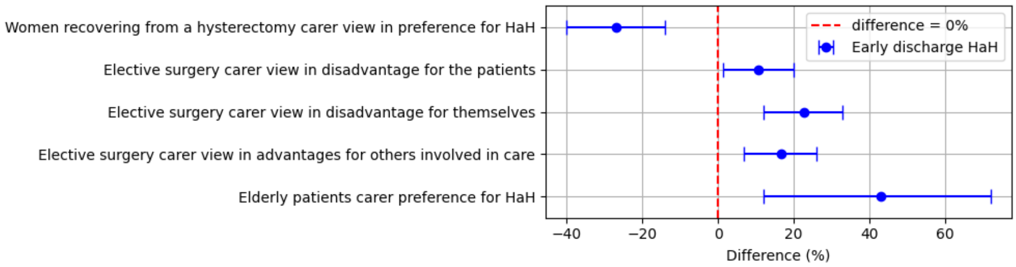


Figure 2.23 Carer preference for HaH care, particularly among carers of women recovering from hysterectomy. Adapted from: Shepperd & Iliffe (2005).

Carers of terminally ill patients receiving HaH care reported greater satisfaction compared to the control group at one month follow-up (P = 0.005). However, by six months, the difference was no longer significant as carers experienced declines in psychological well-being, likely influenced by the deaths of patients, which led to non-homogeneous sample sizes (Shepperd & Iliffe, 2005a).

In admission avoidance schemes, trials recruiting patients with mixed medical conditions, carers in the HaH group generally expressed higher satisfaction compared to those in the hospital group. In one trial, HaH carers rated their satisfaction as "excellent" on a four-point scale, with a 0.8-point higher mean satisfaction score than the hospital group (P < 0.0001), though response rates were lower for hospital carers (27% vs. 55% for HaH) (Edgar et al., 2024; Shepperd & Iliffe, 2005a). Another trial involving semi-structured interviews found that, while in-patient hospital care could relieve some caregiving burdens, carers expressed anxiety and stress related to visiting their relatives, making HaH care the more satisfactory option (Edgar et al., 2024; Shepperd et al., 2009).

2.3.3. Healthcare services

2.3.3.1. Staff

Physicians, nurses, radiologists, pharmacists, and physical therapists are frequently involved in in-home services through HaH programs, working closely with both patients and caregivers. Their clinical expertise is essential for understanding the impact of HaH on patients and their informal carers. However, few studies have explored the workforce's perspectives on this model of care. Grande et al. (1999) examined the views of doctors, district nurses, and informal carers in the context of terminally ill patients care but no significant finding in the HaH context was uncovered. (Shepperd & Iliffe, 2005a).

As part of hospitalization avoidance that included patients with a variety of conditions, one study investigated general practitioners (GP) satisfaction with the provided service. The study found a slight negative difference of 0.2 on a 4-point satisfaction scale for GPs in the hospital group compared to the HaH group. However, the response rate was low: with 63% in the HaH group and 37% in the control group responding (Figure 2.24; Edgar et al., 2024; Shepperd & Iliffe, 2005).

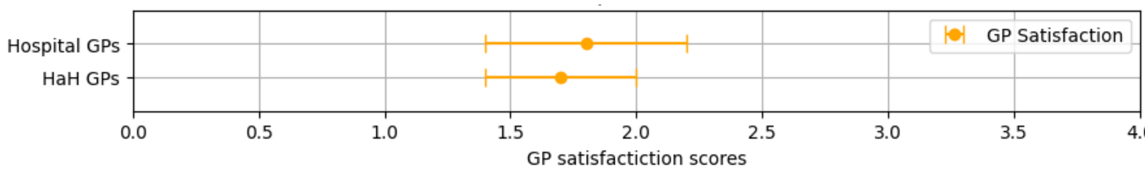


Figure 2.24 GP satisfaction scores for HaH versus hospital care. Adapted from: Edgar et al. (2024) and Shepperd & Iliffe (2005)

2.3.3.2. Length of stay

Shepperd & Iliffe (2005) pooled results from two trials involving elderly medical patients and three trials involving patients recovering from surgery, revealing a reduction in the length of stay for those in HaH care (Figure 2.25). Two additional trials reported a median reduction of 6 days, one for mixed senior HaH patients ($P = 0.002$) and the other for stroke survivors, which showed significant results ($P < 0.0001$) with a 95% confidence interval of -6 to -2 days post-randomization. In this trial, prior to randomization, patients had spent an average of 22 to 25 days in the hospital. Another trial reported a 52% reduction in hospital stay for stroke patients allocated to HaH ($P < 0.008$).

Patients with COPD, women recovering from hysterectomy, and terminally ill patients also experienced significant reductions in hospital length of stay (Figure 2.25). In admission avoidance schemes for patients with various conditions, one trial reported a significant reduction of 6.5 days in median length of stay for HaH patients ($P < 0.03$), while another reported increased length of stay but did not provide data (Shepperd & Iliffe, 2005a).

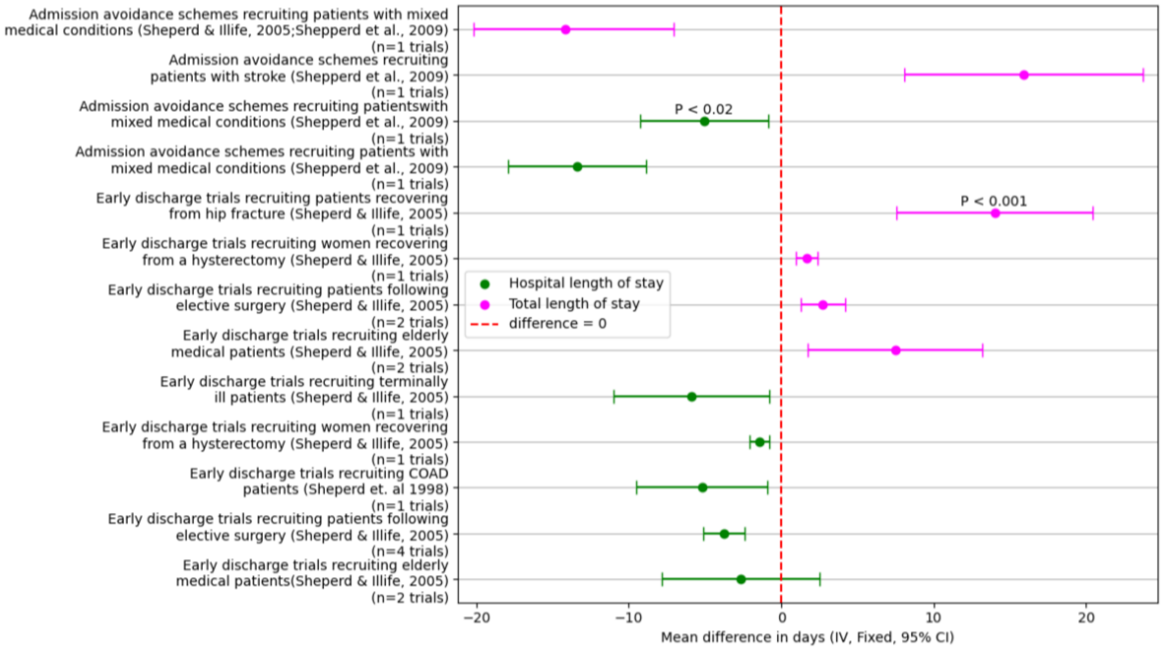


Figure 2.25 Comparison of total length of stay between HaH and hospital care for various patient groups. Adapted from: Shepperd & Iliffe (2005) and Shepperd et al. (2009).

Despite these findings, when Shepperd & Iliffe (2005) combined data from two different studies on elderly medical and surgical patients, the total length of care (including hospital and home care days) showed a significant increase for the HaH group (Figure 2.25). However, in women recovering from hysterectomy, the total length of care did not differ significantly between HaH and hospital care (Shepperd & Iliffe, 2005a). There is no consensus on the overall effect of total care duration in admission avoidance schemes, as some trials report reductions, others report increases, and some find no change, reflecting variability in patient conditions and local healthcare organization (Edgar et al., 2024; Shepperd et al., 2009; Shepperd & Iliffe, 2005a).

2.3.3.3. Other services

One trial found that elderly adults receiving HaH care had a decreased use of other home care services, such as personalized social support for daily living activities, wellness, and health monitoring, at six weeks follow-up. In contrast, a study focused on COPD patients showed an increase in referrals for social support while they were receiving HaH care (Figure 2.26; Shepperd & Iliffe, 2005).

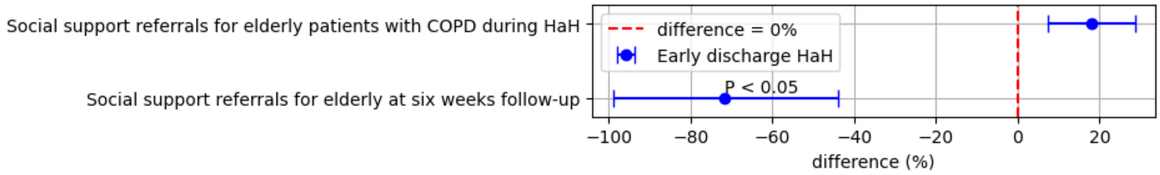


Figure 2.26 Social support referrals for elderly patients with different conditions. Adapted from: Shepperd & Iliffe (2005).

For stroke survivors, another trial reported that 4% more patients in the HaH group received informal care compared to those treated in the hospital, amounting to 979 hours (SD 1749) versus 846 hours (SD 1549) of care over a 12-month period (Edgar et al., 2024). In a trial involving terminally ill patients, out of 15 services analysed, a significant difference was found only in the use of outpatient services, including consultations, therapies, diagnostics, and minor surgical procedures (Shepperd & Iliffe, 2005a).

Finally, for elderly patients with mixed acute conditions under admission avoidance HaH schemes, one trial found no significant difference in the total hours of informal care provided between the treatment group and the control group up to six months of follow-up (Figure 2.27; Edgar et al., 2024).

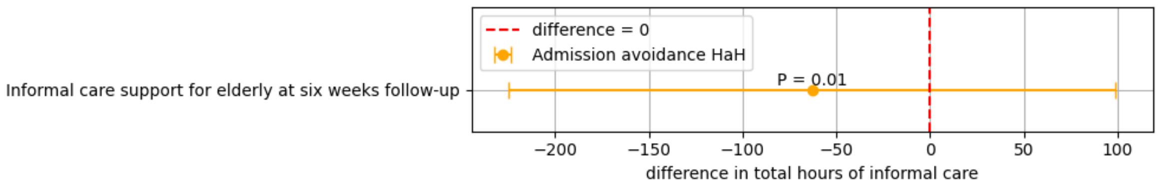


Figure 2.27 Total hours of informal care for elderly patients under admission avoidance HaH schemes at six weeks follow-up. Adapted from: Edgar et al. (2024).

2.3.3.4. Costs

HaH schemes generally appear to reduce costs compared to traditional hospital care, especially from the healthcare service perspective. However, many studies fail to detect statistically significant differences between groups due to variability in labor costs, resources, and patient demand, which differ across and within countries. For instance, Shepperd et al. (1998) found no significant cost differences between HaH and hospital care for patients recovering from hip or knee replacements, except for women following hysterectomy, where HaH became more cost-effective with reductions in hospital stay.

Caplan et al. (1999) found hospital care to be more expensive overall in Australia, but comparisons were limited as some HaH costs, such as GP and nurse coordinator expenses, were not accounted for. While other studies, like those by Echevarria et al. (2018), Jones et al. (1999), and Shepperd et al. (2021) attempted comprehensive resource and cost estimations, there remains complexity in accurately assessing HaH-related costs. Ultimately, cost differences between HaH and hospital care are minimal, and the true value of HaH may lie in its personalized care and health benefits rather than cost savings alone.

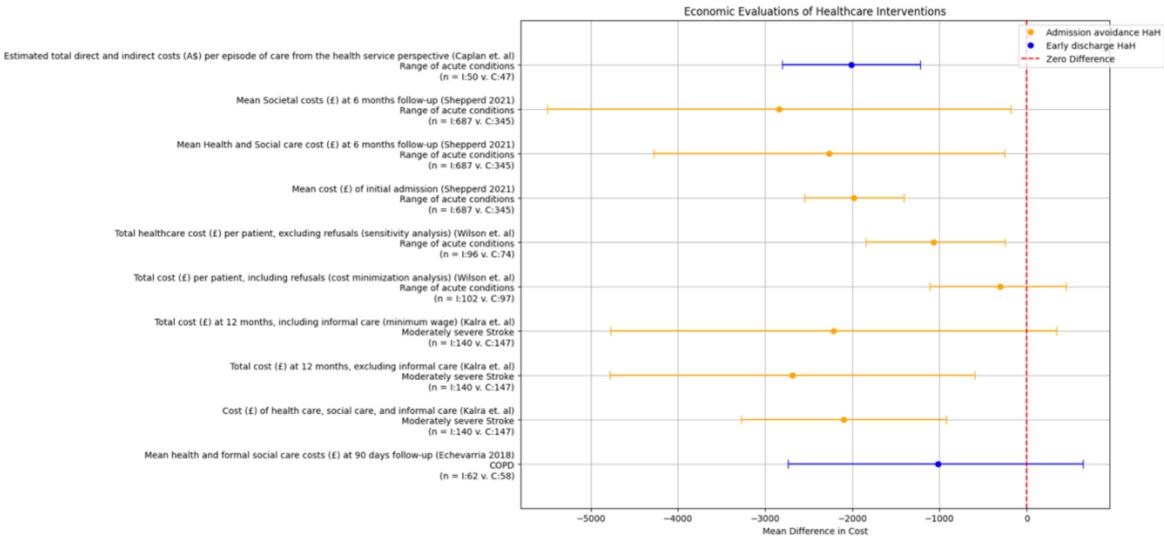


Figure 2.28 Comparison of economic evaluations between HaH schemes and hospital care. Adapted from: Echevarria et al. (2018; Edgar et al. (2024); Gonçalves-Bradley et al. (2017); Shepperd et al. (1998); Shepperd & Iliffe (2005).

2.4. Organizational Structure of HaH

HaH can respond to a large number of acute medical pathologies and help release beds, if properly established, it can avoid problems inherent to conventional hospitalization (Scott, 2010). The ultimate goal is to release so many beds that the needed capacity of beds is reduced, allowing patients to have a holistic service user-centred approach, and enjoy more privacy. To expand and achieve the desired impact, HaH programs need to overtake many challenges: service definition, effective organization, planning and resourcing, as well as efficient interaction with the target population (Rossi et al., 2018). Integrating strategies to enhance communication and operational performance can contribute significantly towards achieving the primary objective of HaH, which is identifying the most suitable location for patient care, improving their quality of life, and optimizing the utilization of hospital resources.

2.4.1. Programme configurations

Two forms of HaH have been established: early discharge and admission avoidance. Early discharge supports patients, by referral of the responsible physician, who have already been admitted as an inpatient, to go home earlier than usual to complete acute or subacute care in their home, thereby partially substituting hospitalization (Lim et al., 2021). Admission avoidance fully substitutes brick-and-mortar hospitalization, providing hospital-level care in the patient’s home to patients referred by a general practitioner in a community-based health centre or in HBPC programs, or in a hospital emergency department (Edgar et al., 2024). Both systems allow patients to be transferred to a hospital at any time if they desire or if their health requires so. An integrated approach to these two arrangements may improve the number of eligible patients (Truong & Siu, 2024).

While most patients come from internal medicine inpatient and emergency services (Chan, 2022), irrespective of the patient's origin, it is crucial that communication between the previous service the patient has transited from and the current service occurs. The referring physician must be apprised of the patient's progress, and the HaH team must have a thorough understanding of the patient's current state of health, thus facilitating the exchange of insights.

Once discharged from HaH, patients may require ongoing skilled care in their homes, which can be made available through HBPC community services (Chen et al., 2024; Truong & Siu, 2024). This collaboration between different services is essential for the better usage of intersecting resources and information (Cotta et al., 2001). Table 1 presents the principal differences between each service that provide important insights about which or when should a patient be allocated to each of these services.

Table 1 Comparison of different services[1] available in the community for providing care with different levels of demand.

	Early discharge	Admission avoidance	Hospital	HBPC
Goal	Accelerate discharge from hospital; Continue treatment at home.	Prevent hospital admission by providing equivalent care at home.	Provide comprehensive complex care for acute and chronic conditions.	Support independence; Prevent hospital readmission; Manage chronic conditions; Prevention; Facilitate timely discharge from the hospital
Patient Identification and evaluation	Within the hospital inpatient units. Criteria based on medical stability, and specific care needs	Emergency department or medical admissions unit; Ambulatory setting; Directly from the community after assessment by primary care physician	Emergency department; Directly from the community; Comprehensive intake process for all presenting conditions	Post-discharge hospital or health centre; Community centres. Assessment of long-term care needs and community resources
Patient Eligibility	Stabilized condition requiring continuation of acute care manageable at home	Patients with acute-level stable conditions at risk of hospitalization but manageable at home	Broad, includes patients needing intensive and specialized care	Generally elderly, chronic patients, post-discharge follow-up
Services made available	Acute-level care specific to the condition; Finish a course of intravenous treatment that cannot be administered by the patient; Post-surgery recovery; Medical treatment monitoring; Rehabilitation	Immediate acute-level care specific to the new or exacerbated condition; Medical treatment provision and monitoring; Dependency on the medical team from treatment	Non-exclusionary, complex, intensive and specialized treatments, therapies and surgeries; Includes acute and chronic diseases	Non-acute ongoing treatment; Maintenance therapy; Social services; Rehabilitation; Self-care by the patient such as self-administration of an intravenous infusion;
Durability of care	Short- to medium-term care, focused on acute care continuation with potential for ongoing management.	Short- to medium-term care, focused on stabilization with potential for ongoing management.	Defined by treatment completion. Short- to long-term care.	Long-term care focused on sustained care and support
Cost	Reduces cost by shortening hospital stays	Potentially avoids costly hospital admissions	High due to comprehensive and specialized services	Cost-saving by reducing hospital readmissions; ongoing support by moderately specialized staff.
Outcome metrics	Readmission rates; Mortality rates; Length of stay; Escalation of treatment; Patient and Carer satisfaction.	Admission rates; Mortality rates; Length of stay; Health stabilization; Patient and Carer satisfaction;	Survival rates; Complications after admission; Disease-specific outcomes.	Quality of life; Functional status; Patient satisfaction

As previously discussed, HaH configurations are characterised by significant heterogeneity due to the numerous variables involved. Table 2 outlines best practices identified in the literature, aimed at mitigating disparities between settings and providing

[1] Information accessed through different sources: Dal Bello-Haas et al. (2023); Leong et al., (2021) and Truong & Siu (2024).

recommendations to enhance care delivery and facilitate the expansion of this model. Critical decisions in HaH domain are influenced by regulatory frameworks and resource availability. The allocation of resources—such as healthcare professionals, consumables, medical equipment, and logistics—determines the program's extent and scope.

Redjem and Marcon (2016) identify three classes of resource management based on the level of resource integration used to deliver care activities: (1) *The unintegrated model*, which relies heavily on external human resources to the management structure; (2) *The semi-integrated model*, which combines a dedicated management structure for activities, while outsourcing the remaining tasks; and (3) *The quasi-integrated model* which employs an internal team primarily focused on HaH activities, although it still requires collaboration with other hospital and post-hospital services.

Table 2 Factors affecting the definition of service and proposed framework.

	Characterised by	Recommended Outline	Examples	
Patient Condition and Needs	Type and severity. Existing comorbidities. Functional status.	Stable clinical criteria that can be easily treated at home in a short to medium period. Assistance/Ability to perform activities of daily living. Identification and enrolment on time.	COPD Asthma Stroke Cellulitis Congestive heart failure exacerbation Pneumonia Dehydration Acute renal failure	Urinary tract infection Deep venous thrombosis Pulmonary embolism Osteoarthritis Hypertensive emergency Infectious diseases Post-surgery recovery Type II diabetes Skin ulcers or wounds
Treatment Requirements	Intensity and complexity of treatment.	Treatment protocols well-established by a multidisciplinary clinical team. Customised design of treatment and resources by a specialized doctor or team. At least daily in-person visit by a clinical team member. Adequate post-acute transition planning.	Intravenous medication Respiratory treatments Oxygen supplementation and titration Phlebotomy Wound care	Anticoagulation therapy Physical and occupational therapy Chronic CPAP/BiPAP Homebased: Xray, ultrasound, Electrocardiograms
Healthcare Provider Resources	Availability, coordination and adaptiveness of resources and their expertise. Multidisciplinary teams with positive dynamics.	Comprehensive management arrangements to support effective, safe, consistent, and accountable working practices, while adapting the reimbursement system to match workload and resource requirements dictated by the complexity of caseload. Individualised and situational appropriate care, education and support to patients and caregivers. Supports transition from the hospital and after dismissal from HaH.	Doctors including specialty general practitioners Nursing staff at different bands Pharmacists Physiotherapists Nutritionist	Occupational therapists Social workers Paramedics Other allied health professionals Technology and equipment Logistics and Support Services
Technology and Equipment	Availability and technical specifications and functionalities.	Transportability and adaptiveness to the homebound. The response capacity increases with the variety and adaptability of the equipment. 24/7 access to clinical team backed up by hospital-based and emergency services.	Remote monitoring devices Infusion pumps Nebulizers Oxygen concentrators	IV pole Specialized mattresses Telemedicine and IT resources Laboratory monitoring equipment
Home Environment	Social criteria.	Suitability for providing medical care. Social care and support based on patient and carer needs.	Space, cleanliness, accessibility, and, if necessary, the presence of a caregiver	
Logistics and Support Services	Geographic criteria.	Maximum 30-minute distance. Frequent home visits with maximum respect to patient preferences and minimum intrusion of private life and space.	Transportation for punctual examinations. Coordination with pharmacies, and access in case of emergency.	Transport of health professionals, delivery, and handling of supplies, testing samples and medication.
Regulatory Policies	Legal frameworks and reimbursement policies set by healthcare authorities and insurers.	Legally recognition of the HHU. Keeping medical costs and treatment similar to hospital's.	Health insurance (patient perspective). Legal constraints and requirements (HHU perspective).	
Patient Preferences	Patient choices and comfort level with receiving care at home.	Patient and caregiver informed consent. Adjust treatment to patient preferences including emotional support.	Preference for in-person visits vs. telehealth. Visits performed by nurse and doctor of election.	

2.4.1.1. Admission and exclusion criteria

In the early days of HaH, admission criteria were based on diagnosis (Leff et al., 1997). Today, there's a shift to clinical service-based criteria which include the treatments available by the HHU to perform at home (Truong & Siu, 2024). However, for patients demanding complex and specialised treatment, such as oncologic and paediatric care, some domiciliary acute care HaH providers limit their admission and adjust the criteria to these specific target conditions (K.Chen et al., 2024). Regardless of the available resources or the program's setup, the patient is evaluated through a range of clinical, social and geographic admission criteria (Lim et al., 2021; Norma No.020/2018, 2018).

Clinical criteria include a wide range of pathologies, from acute infectious pathologies to postoperative care or even incurable progressive diseases in the terminal phase. As long as the patient is transient, stable, and does not require diagnostic or psychiatric investigation (Norma Nº 020/2018, 2018; Shepperd et al., 2009), he falls into the field of action of HaH. Some clinical criteria include age threshold (Patel & West, 2021).

Social criteria imply the acceptance and filling of an informed consent by the patient and eventual informal caregiver; adequate carer support, which can be optional if the patient is independent for ADL; and a home with basic hygienic, sanitary and safety conditions that allow the management of the patient's clinical situation; some schemes require the patient to have insurance or funding references (Chen et al., 2024).

Geographic criteria rely on residence location that must be within the permitted area of operation of the HHU. This delimitation is part of the districting problem (Figure 2.30) and is a very important decision because it involves the travels of the healthcare team that should befall promptly in the case of a worsening event of the clinical condition of a patient, usually further than 50 Km distance are excluded but the limiting boundaries are defined by each HHU (Maniaci et al., 2024; Norma No. 020/2018, 2018).

Cotta et al. (2001) argued that the most appropriate way to define eligible patients for HaH is to apply epidemiological and sociodemographic criteria based on the characteristics of the reference population and hospital or health centre in the geographic area, in place of the initial diagnosis-based criteria. They specifically separate diagnosis-based criteria into 3 groups: acute situations; exacerbated chronic processes; and surgical processes. Table 3 synthesizes the basis criterion identified in literature (Chan, 2022; Cotta et al., 2001; Levine et al., 2020; Norma No. 020/2018, 2018; Wachtel & Gifford, 1998).

Table 3 Inclusion criteria

Clinical Criteria	Social Criteria	Geographic Criteria
Transient Stable Inpatient-level condition Vital signs within normal limits Functional ability to perform ADL Non-depressive symptoms	Voluntary acceptance of HaH with informed consent signature Accepted payer source Adequate carer support Home with basic hygienic-sanitary conditions that allow adequate care (area, electricity, running water, AC/heat, refrigeration, bathroom)	30 min or 30 miles (≈48Km) maximum distance from hospital

Apart from the vast inclusion criteria, exclusionary parameters aid the correct identification of patients by narrowing available options. Clinical exclusionary criteria may be defined by regulations that prohibit some practices to be performed outside the hospital like blood transfusion and other intravenous or intramuscular therapies (Levine et al., 2020). Patients requiring continuous monitoring or those at risk of transfer to the hospital may also be excluded. Sometimes, professionals with their clinical eye can adapt difficult treatments or medications to be provided at home and adjust them, for example, medications that demand short intervals of administration can be replaced with other comparable options that can be taken fewer times a day. Moreover, patients requiring intermediate or intensive care would not qualify for a standard HaH program since these patients are usually in unstable health conditions and demand rapid personal access to the HaH team or transfer to the hospital (Truong & Siu, 2024). Patients with dependence on illicit substances or alcohol, mental, physical, or emotional incapacity including suicidal ideation, psychomotor agitation, acute psychosis and diseases with epidemiological risk are also excluded (Norma No. 020/2018, 2018).

Social exclusion criteria include not having a telephone at home that allows contact with the healthcare team in case of complications, neglected patients, patients under police custody, or residing in a facility that provides onsite medical care represent the most common embargoes for HaH. Geographical locations where temperature extremes are experienced and import risks to health exclude patients who do not have working heat or working air conditioning on a seasonal basis (Levine et al., 2020; Maniaci et al., 2024).

Table 4 Exclusion criteria based on different literature. IV stands for intravenous.

Clinical Criteria	Disease-specific Clinical Criteria		Social Criteria	Geographic Criteria
Regulatory excluded practices (IV pain medication) Alcohol or drug addiction Continuous monitoring necessity (Telemetry) Intermediate or intensive care provision Potential need of rapid transfer to hospital Hemodialysis or peritoneal dialysis Surgery in the last 24h or the next 48h Unstable mental illness Acute cardiovascular events Non-invasive positive pressure ventilatory support ICU patients Acute hemorrhage Acute psychosis Endoscopic procedures Cardiac stress test Cardiac drip medication Unstable arrhythmia Severe pulmonary hypertension Physical exam monitoring for neurological status IV drip medications	For Pneumonia: Most recent CURB-65 score >3 Most recent SMRT-CO score >2 Absence of clear infiltrate on imaging Cavitary lesion on imaging Pulmonary effusion of unknown etiology Oxygen saturation <90% or oxygen therapy >5L For heart failure: Has a left ventricular assist device GWTG-HF (>10% in-hospital mortality) or ADHERE (high risk or intermediate risk 1) For complicated urinary tract infection: Absence of pyuria Most recent qSOFA score >1 For other infection: Most recent qSOFA score >1 For COPD: BAP-65 score >3 Acute cardiovascular events	For asthma: Peak expiratory flow <50% of normal: exercise caution For diabetes and its complications: Requires IV insulin For hypertensive urgency: Systolic blood pressure >190 mm Hg Evidence of end-stage organ damage For atrial fibrillation with rapid ventricular response: Likely to require cardioversion New atrial fibrillation with rapid ventricular response Unstable blood pressure, respiratory rate, or oxygenation Despite IV or calcium-channel blockade in the ED, HR remains >125 beats/min and systolic blood pressure remains different from baseline <1 h has elapsed with HR <125 beats/min and systolic blood pressure similar to or higher than baseline	No voluntary acceptance of HaH by patient or its mandatory caregiver Under 18 years old Requires 24/7 assistance for ADL without available caregiver Domestic violence screen positive In police custody Resides in facility that provides onsite medical care Receiving methadone requiring daily pickup of medication	Home outside the defined distance radius

2.4.2. Service delivery

The activities on the HaH domain start by a referral by the doctor responsible for the patient case or members of the HHU manually reviewing the patient list or the hospital ward looking for potentially eligible patients (Maniaci et al., 2024). Subsequently, a social worker ensures that the patient meets social criteria, and a specialised doctor or nurse from the HHU evaluates the clinical admission criteria according to the *legis artis*. If the patient meets inclusion and none of the exclusion criteria, a nurse will contact them to explain the main characteristics of the program (Patel & West, 2021; Norma No 020/2018, 2018). A decision is taken, either the patient and the informal caregiver accept or reject the transfer to HaH. In case of agreement, a doctor and a nurse visit the home and make the last inspection, guaranteeing that the environment gathers the right conditions for recovery. The patient and their cohabitants are instructed to identify warning signs, administer home treatments, and any doubts are addressed promptly. The patient's hospital clinician is required to maintain regular contact with the HaH team. If hospital appointments are needed, the HaH team is responsible for providing transportation (Cotta et al., 2001). In settings with superior technological resources, it is possible to conduct examinations via video and by transmitting stethoscopes, whereby the sounds detected during the examination in the home can be recorded and listened to, asynchronously, by the remote team, thereby granting patients the same access to specialised care as traditional hospitalised patients merely in their homes (Truong & Siu, 2024). The hospital dispenses any additional supplies required for the patient's treatment via the HaH nurses, who place orders on their behalf, transport to the patient home all resources needed including the entire pharmacopoeia, provide therapies designed by the HHU doctor, oversee the training, and record the information for each patient. The report of the patient's homebound status, state of mind, needs, health condition progression, and reaction to medication in daily meetings ought to be a settled practice on any HaH agenda, so that the multidisciplinary team can discuss important insights into the most adequate treatment. Based on this evidence, doctors adjust the treatment and establish the frequency of visits, which is largely determined by the medication schedule, and check for further investigations, such as hospital examinations or the patient's readmission to the hospital in case of deterioration. Access to the clinical team is provided around the clock through a designated contact number or, in some cases, a tablet equipped with standard communication forms, including secured text services. Additionally, the patient is provided with a medical alert device that monitors various vital signs, and a care plan outline to follow (Truong & Siu, 2024).

Independently of the methods used, it is essential to design care according to the patient's acuity and needs, ensuring seamless integration with traditional brick-and-mortar healthcare services and maintaining a high level of communication between service users and practitioners. This guarantees that goals are aligned and achievable. Additionally, it is crucial that both the patient and informal caregiver are fully aware of their therapy's implications, especially when part of the care is delegated to them. The role of the caregiver is therefore demanding, also requiring special attention and support, especially in situations of aggravated dependence or the need to handle certain medical devices (such as nasogastric tubes, catheters, among others). The direct connection between the healthcare team, the patient, and their caregivers outside the hospital environment, while maintaining safety and quality of care, reinforces the humanization of medicine, enhances the perception of the disease, and creates unique opportunities for personalized education and health promotion for the patient or family.

A process model outlining the main required functions on a HaH setting and proposing the workflow and distribution of tasks among professionals is presented in Figure 2.29.

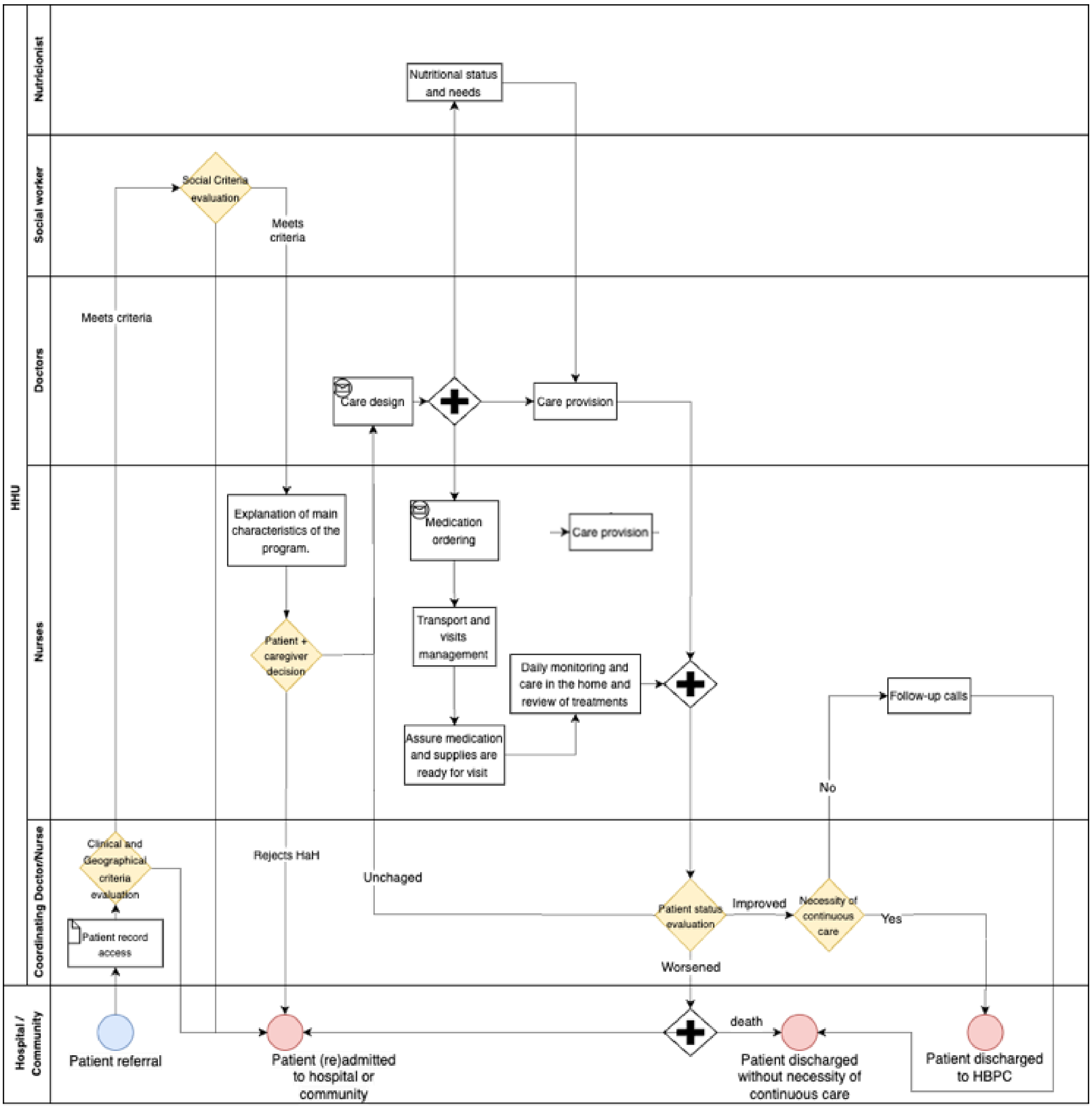


Figure 2.29 General HaH workflow from patient referral to discharge with distribution of tasks among each HHU professional.

The "care provision" process, depicted in Figure 2.29, is particularly interesting from an operational research perspective due to the complexity involved in optimizing healthcare resources. Grieco et al. (2021) provided a comprehensive review of the tactical problems and methodologies related to HaH operational management, including staff allocation, visit scheduling, and routing. The dynamic nature of HaH, with its stochastic daily demand and unpredictable patient needs, requires highly adaptive planning and resource allocation.

From an operations research standpoint, HaH challenges occur at both strategic and operational levels. The strategic level involves decisions such as resource allocation, geographical districting, and balancing workloads across districts, all while adhering to specific constraints like continuity of care. The operational level focuses on day-to-day decisions, including assigning visits to caregivers and optimizing routing.

A key area for minimizing waste and inefficiency is the daily scheduling of healthcare professionals. This includes decisions on which professional should visit which patient, at what time, and what routes they should take. The complexity of meeting physician-specified care requirements and balancing these against logistical constraints makes this a difficult optimization problem (Grieco et al., 2021).

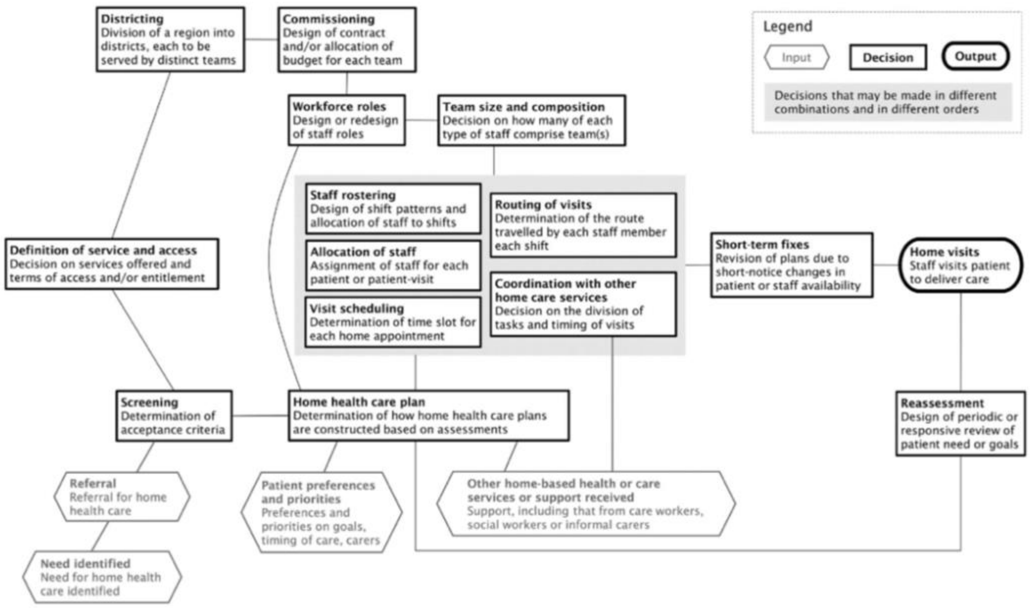


Figure 2.30 Decision problems influencing the configuration and extent of care services in HHUs. Source: Grieco et al. (2021)

2.5. Scheduling and Routing Problems for HaH

Based on the evidence discussed in the preceding chapters, the HaH program aims to provide complex, coordinated healthcare to patients within their homes. This often involves a planning process that includes the allocation of tasks to employees of the HHU, scheduling patient appointments, and determining the travel routes of care workers. The process ensures compliance with regulatory and operational guidelines in a highly dynamic environment. This logistical and operational challenge is commonly referred to as the Home Health Care Scheduling and Routing Problem (HHCSRP). It is a critical component of effectively managing home health care services, ensuring that resources are used efficiently and that patients receive timely and high-quality care.

Recently, there has been a substantial growth in literature on HHCSRP, underscoring its relevance and utility. Nevertheless, the broad range of home care programs and the diverse methodologies used to address HHCSRP make it challenging to comprehensively explore all methodologies tested. Thus, the discussion will concentrate on key strategies that effectively tackle these challenges.

2.5.1. Key Literature and Approaches

The problem was first formulated by Begur et al. (1997) as a Spatial Decision Support System (SDSS) that integrated geographic information system software with scheduling heuristics to design nurses' care agendas. The system took into account patients' availability and requirements, as well as nurses' availability. The resulting tool was user-friendly and customizable, enabling nurses to adjust routes as needed.

Cheng and Rich (1998) consider a semi-integrated model (Redjem and Marcon, 2016; see section 2.4.1) with both part-time and full-time nurses. The solution method employs mixed-integer programming (MIP) and involves a two-phase heuristic algorithm: the first phase simultaneously constructs multiple routes, while the second phase focuses on improving these routes. Additionally, two different formulation approaches are presented: one employs triple-indexed variables, while the other uses double-indexed variables.

Eveborn et al. (2006) investigate a heuristic-based tool for assigning patients and scheduling care visits. Their approach effectively utilizes the Set Partitioning Problem combined with Repeated Matching techniques. Moreover, they incorporate specific constraints related to domestic services and language knowledge to be assisted during each visit, in addition to nursing duties. Each staff member has unique skills, and patient’s staff member preferences must be satisfied. Their primary goals seek minimisation of transportation time and enhancement of patient satisfaction.

Steeg and Schröder (2007) propose a hybrid solution combining Constraint Programming (CP) and Adaptive Large Neighbourhood Search (ALNS). This approach leverages the precision of CP for initial feasibility and the flexibility of ALNS for iterative improvement, aiming to optimize nurse-patient loyalty, minimize nurse costs, and reduce travel distances within a multi-period scheduling framework.

Akjiratikarl et al. (2007) present a meta-heuristic approach based on a Particle Swarm Optimization (PSO) algorithm for home care workers scheduling. The methodology combines an Earliest start time priority and Minimum distance assignment heuristics for a strong initial solution, with the global search capabilities of PSO and local improvement procedures for refined local searches. Key constraints include time windows, non-splittable activities, and daily work limits. Objectives are to minimize total travel distance, adhere to time windows, and optimize staff utilization. The study acknowledges uncertainty by optimizing parameters for robust performance across scenarios, demonstrating significant efficiency improvements compared to manual and software-based scheduling methods.

Fikar & Hirsch (2015) use a matheuristic solution approach which identifies feasible walking routes, reducing the dependency on vehicle transportation. An initial solution is constructed using a biased-randomized savings heuristic, and optimized with a tabu search algorithm, ensuring synchronization and adherence to constraints to minimize travel and waiting times.

Naderi et al. (2023) develop a comprehensive approach for multi-period staffing, assignment, routing, and scheduling in home care services. Using a Mixed Integer Linear Programming (MILP) model, the methodology aims to minimize fixed and overtime costs while adhering to operational constraints. The model addresses uncertainty in service and travel times through a robust optimization framework incorporating hybrid interval and polyhedral uncertainty sets. A novel logic-based benders branching-decomposition algorithm enhances computational efficiency by using the statuses of subproblems (infeasible, unknown, sub-optimal) to eliminate ineffective nodes.

Varas et al. (2024) introduces complexity to the problem by addressing not only the assignment of patients to specific teams and determining service start times efficiently, considering constraints like synchronized visits, multiple time windows, and mandatory lunch breaks, but by additionally including the perishability of biological samples that demand immediate return to the hospital to prevent degradation. To tackle this, the study proposes a hybrid solution incorporating a MILP model to handle these constraints, combined with a two-stage heuristic approach. This approach begins with a greedy heuristic based on the push-forward insertion method, followed by a local branching improvement heuristic, providing high-quality solutions within reasonable computational times.

The overarching problem is commonly equated to a Vehicle Routing Problem with Time Windows (VRPTW). The VRPTW involves multiple vehicles adhering to specific time constraints to determine optimal routes with the caregivers being defined as vehicles and the pick-ups as visits. Ultimately, the choice of algorithm and its methodology depends on the specific goals and requirements of each problem, emphasizing the importance of tailoring the approach to effectively address the unique challenges posed by each scenario. In terms of complexity class, which gauges the computational effort required in terms of time and space relative to the input size, HHCRSP is an extension of the Vehicle Routing Problem which has been proved to be NP-hard (Archetti et al., 2005). NP-hard (non-deterministic polynomial-time hard) problems are characterized by the absence of known polynomial-time algorithms, necessitating significant time to derive optimal solutions, particularly when the instance size is substantial. Additionally, various features related to the HHU, patients, or caregivers must be taken into account in the HHCRSP formulations. These features increase the complexity of solving the HHCRSP, as each is modelled either as a constraint or an optimization criterion in the objective function. Given this complexity, heuristic approaches are commonly employed and are considered the most relevant method to address this problem effectively, as demonstrated by Redjem and Marcon (2016). However, each configuration is unique, necessitating a tailored resolution.

2.5.1.1. Planning Horizons and Solution methods

The planning horizon in HHCSRP is classified as either single-period or multi-period. The single-period problem focuses on a single working day or a single future period without considering multiple periods simultaneously (Lanzarone & Matta, 2014). In contrast, the multi-period problem extends over multiple days, weeks, or even months. Information regarding single-period planning is deterministic, whereas multi-period planning often relies on forecasts. This implies that decisions regarding the planning horizon depend on both the quality and availability of information accessible to the HHU (Fikar & Hirsch, 2017).

The solution methods for HHCSRP vary and include exact methods, approximative methods such as heuristics and metaheuristics, and hybrid solutions. Hybrid solutions can be broadly categorized into two types: general hybrid methods and matheuristics. General hybrid methods integrate exact methods with heuristics or metaheuristics. Matheuristics, on the other hand, are a specific subclass of hybrid methods that deeply integrate mathematical programming techniques within a heuristic or metaheuristic framework. The key distinction is that matheuristics use mathematical models as an inherent part of the heuristic or metaheuristic process, rather than merely combining the two approaches sequentially. This allows matheuristics to more seamlessly leverage the strengths of both exact methods and heuristics, resulting in more efficient and effective solutions for complex optimization problems. Each approach offers different advantages depending on the complexity and requirements of the problem.

Exact methods explore the entire solution space systematically, aiming for optimal solutions. These methods are employed in environments that often involve small to medium-sized instances. In the context of HHCRSP, the problems are commonly modeled as Integer Linear Programming (ILP) (Bachouch et al., 2011; Nasir et al., 2018) or MILP (Kandakoglu et al., 2020; Naderi et al., 2023). Linear solvers are typically used to find the solutions. Additionally, other optimization techniques are employed to leverage constraint programming principles to prune the search space and solve subproblems more effectively, such as the Logic-Based Benders Decomposition proposed by Naderi et al. (2023).

Approximative methods are often employed to avoid the extensive exploration times exact methods take to run the search space, besides they can be computationally infeasible for large instances. Heuristic methods are designed specifically for each problem to produce good enough solutions quickly, even if they are not guaranteed to be optimal. Common heuristic methods for HHCRSP include repeated matching (Eveborn et al., 2006), greedy algorithms (Lanzarone & Matta, 2014; Redjem & Marcon, 2016; Vieira et al., 2022), local search, constructive heuristics (Redjem & Marcon, 2016; Vieira et al., 2022), improvement heuristics (Akjiratikarl et al., 2007; Begur et al., 1997), among others. Metaheuristics are higher-level procedures designed to guide other heuristics to explore the solution space more effectively which may only find good solutions within a reasonable time. Common metaheuristic methods include PSO (Akjiratikarl et al., 2007), Genetic Algorithms (Makboul et al., 2024; Rebordão, 2021) and Memetic-Ant Colony Optimization (Decerle et al., 2019).

Given the complexity of the problem, hybrid solution methods are typically employed. Different strategies are employed and vary from problem to problem. In the given gathered literature, approaches are: MILP with constructive heuristics (Begur et al., 1997), Local Search and Improvement heuristics (Cheng & Rich, 1998; Varas et al., 2024); CP with ALNS (Steeg & Schröder, 2007); Branch and Price with Greedy algorithms, adapted k-means clustering, dynamic cluster expansion and Pruning heuristics (Rasmussen et al., 2012); ILP and Set Partitioning with Tabu search and an extension of the Savings heuristic (Fikar & Hirsch, 2015); ILP with Advanced Local and Neighborhood search strategies (Yalçındağ et al., 2016); ILP with Pattern-based heuristics, clustering and Sequence preservation (Cappanera et al., 2018); Non-dominated Sorting Genetic Algorithm II (NSGA-II) with local search heuristics for the first stage and a MILP model for the second stage (Makboul et al., 2024).

Table 5 Planning horizon and Solution method

Article	Planning horizon		Solution method		
	SP	MP	Exact	Heuristics/Metaheuristics	Hybrid/Matheuristics
Begur et al. (1997)		●			●
Cheng & Rich (1998)	●				●
Eveborn et al. (2006)	●			●	
Steeg & Schröder (2007)		●			●
Akjiratikarl et al. (2007)	●			●	
Bachouch et al. (2011)	●		●		
Rasmussen et al. (2012)	●				●
Lanzarone & Matta (2014)	●			●	
Fikar & Hirsch (2015)	●				●
Redjem & Marcon (2016)		●		●	
Yalçındağ et al. (2016)		●			●
Cappanera et al. (2018)		●			●
Nasir et al, (2018)		●	●		
Decerle et al. (2019)	●			●	
Kandakoglu et al. (2020)	●		●		
Vieira et al. (2022)		●		●	
Naderi et al. (2023)		●	●		
Makboul et al. (2024)		●			●
Varas et al. (2024)		●			●
Count 19	9	10	4	6	9

2.5.1.2. Constraint consideration

Constraints play a crucial role in ensuring the delivery of high-quality care while optimizing the efficiency and effectiveness of the scheduling and routing process. Addressing these constraints effectively is paramount for optimizing home healthcare delivery, requiring a thorough understanding of patient needs, caregiver capabilities, and logistical considerations. Thus, primary constraints in HHCRSP are categorized into three main groups: patient-specific, caregiver-specific, and visit-specific constraints.

Patient-specific constraints primarily focus on service time windows (TW) and patient preferences (P). Service time windows (TW) can be rigid if dictated by the patient's medical condition, requiring visits at specific times to comply with medication timings. Alternatively, they can be flexible, accommodating the patient's availability and personal schedule. Patient preferences (P) introduce a level of personalization into the scheduling process, often attracting penalties if violated, and extend beyond continuity of care to include compatibility with the caregiver. This encompasses the subjective aspects of care, such as the patient's comfort and satisfaction with the assigned caregiver.

Caregiver-specific constraints include working time (WT), breaks (Br), district limitations (D), overtime (O), and workload balance (WB). Working time (WT) is a critical constraint, defining the periods during which caregivers are available for visits. This ensures efficient scheduling, while addressing other constraints such as compliance with regulatory guidelines, and balanced workloads to prevent caregiver burnout and underutilization. Breaks (Br) are mandated by regulatory standards, typically setting a maximum duration of continuous work without a break. District limitations (D) involve dividing service areas into sub-areas, with each patient assigned to a specific sub-area and caregivers to one or more. Overtime constraints (O) can be rigid, imposing strict maximum daily work hours, or flexible, allowing for overtime with associated penalties and caps to manage excessive working hours. Ensuring workload balance (WB) is vital as it promotes an equitable distribution of work among caregivers. This balance can be measured by the number of visits or total working time.

Visit-specific constraints encompass depot constraints (SD vs. MD), skills requirements (Sk), continuity of care (CC), visit frequency (VF), visit patterns (VP), synchronization (Syn), and precedence (Pr). Depot constraints address the starting and ending points of visits, with single depot models (SD) centralizing visits at a hospital and multiple depot models (MD) allowing for various starting and ending locations, enhancing flexibility and routing efficiency. Existing literature on this matter is associated with HBPC corporations that allow nurses to start and end their visits at home or that have subsidiaries extended over different geographic locations. Skills requirements (Sk) ensure that caregivers possess the necessary qualifications to meet patient demands, aligning professional competencies with patient needs. Continuity of care (CC) aims to minimize the number of different caregivers assigned to a patient over multiple periods, fostering stable caregiver-patient relationships and ensuring consistent, high-quality care. Visit frequency (VF) dictates the regularity of care visits within the planning horizon, ensuring timely care based on the patient's needs and care plan. Visit patterns (VP) consider the duration of visits and temporal dependencies, maintaining consistency with other constraints such as service time windows, patient preferences, and skills requirements. Synchronization (Syn) is essential for patients needing simultaneous visits from multiple caregivers, ensuring coordinated and comprehensive care delivery. Finally, precedence constraints (Pr) ensure that care is administered in a logical and medically appropriate order.

Table 6 provides a comprehensive overview of these constraints, highlighting which specific constraints are addressed by various authors in the field. This detailed tabulation not only serves as a reference for understanding the scope and focus of existing literature but also identifies core-constraints in HHCRSP such as WT, Sk and TW.

Table 6 Most considered constraints.

Article	**Visits**								**Patient**		**Caregivers**				
	MD	SD	CC	Sk	VF	VP	Syn	Pr	P	TW	WT	Br	D	O	WB
Begur et al. (1997)	●			●	●					●	●				●
Cheng & Rich (1998)	●									●	●	●			
Eveborn et al. (2006)	●		●	●				●	●	●	●	●	●		
Steeg & Schröder (2007)					●	●				●	●				
Akjiratikarl et al. (2007)	●									●	●				
Bachouch et al. (2011)		●	●	●							●	●	●	●	
Rasmussen et al. (2012)	●			●			●	●		●	●				
Lanzarone & Matta (2014)		●	●									●			●
Fikar & Hirsch (2015)		●		●			●			●	●	●			
Redjem & Marcon (2016)		●						●		●	●				
Yalçındağ et al. (2016)		●	●	●			●				●				
Cappanera et al. (2018)		●		●							●				
Nasir et al, (2018)	●		●	●					●	●	●	●	●		●
Decerle et al. (2019)	●			●			●			●	●			●	
Kandakoglu et al. (2020)	●			●						●		●		●	●
Vieira et al. (2022)		●	●	●		●				●					
Naderi et al. (2023)		●									●				
Makboul et al. (2024)		●	●	●			●	●	●	●					●
Varas et al. (2024)		●		●		●	●			●		●		●	●
Count 19	8	10	7	13	2	3	6	4	3	14	14	8	3	4	6

2.5.1.3. Objective function

The objective function represents the main goals to be achieved and is strategically selected to perform accordingly to the algorithm. These objectives can be separated into three main categories: route-related, caregiver-related and patient-related. To accomplish these goals, constraints are incorporated into the objective function, working synergistically. By optimizing the objective function, hospitals can ensure the efficient use of resources, minimize idle times, and maximize productivity. This often involves balancing multiple, sometimes conflicting, criteria such as minimizing costs, maximizing patient care quality, and ensuring staff satisfaction.

Travel-related objectives are the most common in the analysed papers because, as optimizing these objectives directly addresses the routing component of the problem. These objectives are typically categorized in terms of travel time (TT), travel cost (TC), or travel distance (TD).

Caregiver-related objectives encompass considerations such as wages (W), the number of caregivers (#C), working time (WT), waiting time (WaT), Workload Balance (WB), and Overtime (O). Minimizing wages (W) aims to reduce costs associated with caregivers, which can vary based on their profession or experience. The number of caregivers (#C) is included in the objective function to optimise the use of available care workers or to minimise resource usage. Working time (WT) and waiting time (WaT) aim to minimize non-effective working periods, with the latter particularly relevant in scenarios involving time windows and schedule synchronization. Workload Balance (WB) seeks to either maximize workload distribution or minimize workload differences among caregivers. Overtime (O) focuses on reducing labor-related operational expenses.

Patient-related objectives emphasize maximizing patient satisfaction by considering their routines (VTP), aligning caregiver assignments with patient preferences (P), and ensuring continuity of care (CC). These objectives also include minimizing violations such as uncovered visits (UV) or unmet patient time windows (TWV) as soft constraints.

The objective function helps in quantifying these criteria into a single or multiple, manageable goals, enabling the development of schedules that best meet the overall needs. Most of these studies use the weighted-sum approach to unify all objectives into a single objective. Vieira et al. (2022), on the other hand, suggested a bi-objective approach with multiple secondary objectives.

Table 7 Most considered objectives

Article	Route	Caregivers						Patients				
	↓	↓	↓	↓	↓	↑	↓	↑	↑	↑	↓	↓[2]
	TT/TC/TD	W	#C	WT	WaT	WB	O	VTP	P	CC	UV	TWV
Begur et al. (1997)	●											
Cheng & Rich (1998)		●		●			●					
Eveborn et al. (2006)	●							●	●			
Steeg & Schröder (2007)	●	●								●		
Akjiratikarl et al. (2007)	●										●	
Bachouch et al. (2011)	●											
Rasmussen et al. (2012)	●								●		●	
Lanzarone & Matta (2014)						●	●					
Fikar & Hirsch (2015)	●			●								
Redjem & Marcon (2016)	●				●							
Yalçındağ et al. (2016)	●					●						
Cappanera et al. (2018)						●						
Nasir et al. (2018)	●					●	●		●			
Decerle et al. (2019)	●					●						●
Kandakoglu et al. (2020)	●		●				●					
Vieira et al. (2022)				●						●		
Naderi et al. (2023)		●					●					
Makboul et al. (2024)	●					●						
Varas et al. (2024)	●				●							
Count 19												

2.5.1.4. Uncertainty handling

Although many of the analysed papers focus on deterministic planning, it is widely acknowledged that random events introduce uncertainty into at least one parameter of the HHCRSP. Such events include changes in patients' conditions, resource unavailability, and variable service durations, all of which can disrupt service delivery, affect nurses' workloads, and compromise the feasibility of plans. The most critical and frequent events are sudden changes in patients' conditions, which introduce high uncertainty in service demand and complicate resource planning. While deterministic models typically rely on daily planning or flexible parameters adjustments to manage these uncertainties, enabling better management of unforeseen events and more efficient allocation of resources, other approaches incorporate these uncertainties directly into their models. Besides, Davis et al.'s (2014) analysis suggests that the power of most forecasting methods deteriorates when used beyond one week for forecasting.

[2] ↑ maximize; ↓ minimize

For instance, Akjiratikarl et al. (2007), despite focusing on deterministic aspects, acknowledge uncertainties particularly in parameter sensitivity and algorithm robustness. They employ the Taguchi method to identify parameter settings less sensitive to noise, ensuring consistent performance across various scenarios.

Koeleman et al. (2012) employ a Markov decision process (MDP) framework to handle the stochastic nature of personnel planning, capturing randomness in patient arrivals, which follow a Poisson process, and the variability in service durations, which follow an exponential distribution. To address the high-dimensional and computationally intensive nature of the MDP, they propose a trunk reservation heuristic. This heuristic manages uncertainty by reserving specific amounts of service capacity for different classes of patients, ensuring that adequate capacity is available for higher-priority or more urgent cases.

Lanzarone & Matta's (2014) account for uncertainty by considering the stochastic nature of patient demands and nurse workloads. Their model uses probabilistic estimates for demands and incorporates this variability into assignment decisions, creating robust plans that handle variations in patient needs and nurse availability.

Cappanera et al. (2018) address uncertainty in patient demand using a cardinality-constrained robustness framework, where a limited number of uncertain requests are considered per day to ensure feasibility and cost-effectiveness.

Naderi et al. (2023) include uncertainty in service and travel times and develop a robust counterpart using hybrid interval and polyhedral uncertainty sets. This robust model allows decision-makers to incorporate varying levels of risk tolerance, obtaining solutions with different conservatism levels.

In summary, to effectively handle uncertainty in HHCRSP, various approaches are employed. Robust optimization techniques provide solutions resilient to variability, while adjustable parameters fine-tune the model's adaptability, besides, incorporating randomness into models can account for unforeseen changes. Another approach is to allow real-time updates on the routing and to allow direct last-minute modifications in the plans of care, which can be handled by allowing Application Programming Interfaces (APIs) in the model, which permits different programs to communicate in real-time (Begur et al., 1997).

3. PROBLEM DESCRIPTION

This chapter provides a comprehensive overview of the context surrounding the problem, derived from discussions with the managers and providers from a local Portuguese HHU under the auspices of *Unidade Local de Saúde Almada-Seixal*. This specific HHU is located within the *Hospital Garcia de Orta*'s (HGO) facilities. The primary goal was to devise a rapid and optimized method for allocating clients to healthcare professionals.

The team consists of 12 nurses who are dedicated solely to the HHU, as well as 5 doctors, 1 social worker, 1 operational assistant, 1 technical assistant, 1 nutritionist and 2 pharmacists who are also shared with other services. The HHU has a fleet of 4 vehicles at its disposal.

To manage the simultaneous admission capacity of 20-22 patients, the coordinating doctor plans the medical team's shifts at the beginning of each month, considering any other responsibilities they may have, such as the emergency service escalation and consultations. Similarly, the coordinating nurse arranges the nursing staff shifts. The shift arrangements are detailed in Table 8.

Table 8 Shifts of the HHU professionals

	Hours	Professionals available
Morning Shift **Weekdays**	8:00 – 16:00	1-4 Doctors 5 Nurses[3]
Afternoon Shift **Weekdays**	15:30 – 23:00	1 Nurse
Prevention Shift **Weekdays, Weekends and Holidays**	16:00 – 8:00	1 Doctor 1 Nurse
	23:00 – 8:00	1 Nurse

The planning process for assigning medical professionals to patients and determining their respective routes happens during an afternoon meeting at 15:30 one day in advance and after the completion of the morning visits. This meeting serves as both a planning session

[3] Only 4 nurses provide home care to patients, 1 of them provides administrative services and hospital care.

and a handover point between shifts. During this time, based on patient care requirements and clinical stability, the team identifies which patients will be visited by both a doctor and a nurse and which will only require a nurse. If a patient’s condition is unstable, they receive daily doctor visits, potentially with multiple visits per day. For stable patients, only a nurse visits to maintain continuity of care. Patients always receive visits from both a doctor and a nurse on the first and last day of their HaH treatment.

In the morning shift, prior to scheduled visits, the team reconvenes to review each patient's medical and social circumstances. They discuss patient medication, weight, mood, pain, allergies, and lab results from home samples. The team also assesses the need for additional resources, such as specialized equipment. For instance, if changes in a patient’s condition are noted, the plan may be adjusted accordingly, including potential hospital transportation. The medical team then prepares supplies and heads out for the day’s visits, which are primarily conducted during the morning shift.

If a doctor or nurse deems that a follow-up visit is needed in the afternoon, they inform the medical and nursing coordinators, who adjust the plan and address this during the 15:30 meeting. Meanwhile, a doctor and nurse remain at the hospital for assessments and administrative duties, including managing new patient referrals to HaH. If a new patient meets the criteria for HaH and there is availability, they are evaluated, with a mandatory home visit scheduled within the next 24 hours.

3.1. Current Scheduling and Routing approach at the HHU

Currently, the HHU organizes visits based on two main criteria:

1. Responsible doctor
2. Geographical area/location

The first criteria involves grouping patients by responsible doctor, who is to visit the patient accompanied by one of the working nurses. The order of visit is then established based on the second criteria, which is the geographical area. Both criteria are determined manually and rely heavily on the professionals' familiarity with the area. Patients whose doctor is not on call that day are visited by a nurse alone, and scheduling is based exclusively on the geographical criteria.

Efforts are made to include two additional criteria in the visit schedule:

1. Number of visits to be performed on that day
2. Biological sample collection

These additional criteria establish the order for visiting patients. For instance, if a patient is to be visited more than once on that day (but never on the same shift), they should be visited first. On the other hand, if a biological sample for examination needs to be collected, this patient should be visited last to avoid degradation of the sample. The remaining patients are visited in between.

Final considerations concern the frequency of visits and in this regard, patients are visited daily. However, if the patient has an appointment on that day at the hospital, then he will not be visited at the home. Instead, the patient will be assessed at the HHU located inside the hospital and his transportation is either ensured by the ambulatory team or the patient carer.

Currently, there is no consideration for service time windows or patient's preferences. Efforts are made to respect the working time and avoid overtimes, however, breaks are only allowed before and after visits, so visits to patients are made continuously without breaks during the service. District limitations are considered in terms of geographical zones, meaning that visits can be performed only in the district of Almada/Seixal. Patients outside this district are not admitted to HaH. Workload balance is considered in terms of number of patients equal distribution. All professionals performing the visits start and end their routes at the hospital.

Taking into account the previous information, it becomes quite evident that manually distributing tasks leads to significant inconsistency and makes tracking visits cumbersome. Currently, the staff must fill out a paper sheet with the visits carried out, duration and distance covered. This manual method does not allow to schedule visit time windows, that, could enhance patient satisfaction. The current approach makes it difficult to predict whether schedules will be followed. If schedules are not obeyed, the afternoon meeting is delayed, causing the morning shift staff to work overtime and disrupting the subsequent shift's work.

Table 9 Current visit indicators. Source: Relatório e Contas (2022).

Average time spent at the patients' home (min)	Average travel time (min)
34.9	16.3

4. METHODOLOGICAL APPROACH

The problem at hand is a combinatorial optimization challenge focused on efficiently assigning patients to healthcare professionals and determining optimal routing. The primary objective is to ensure that all patient visits are completed within designated working hours while balancing the workload among the healthcare team. To achieve this, a Scheduling and Routing Problem was implemented, aiming to optimize daily staff assignments, establish expected time windows for visits, enhance patient satisfaction, and improve route efficiency by minimizing travel distances and reducing tasks that do not add value for the patient such as planning. A heuristic approach was developed and applied to daily scheduling at the Unidade Local de Saúde Almada-Seixal (see section 3.1). This algorithm was named ULS-AS-SRP.

Heuristic and meta-heuristic methods offer alternatives to exact optimization approaches for complex real-world problems by finding near-optimal solutions quickly, though this often involves sacrificing optimality, completeness, accuracy, or precision (Eiselt & Sandblom, 2000). Even so, given the problem size and the fact that a fast solution was preferred, an adapted heuristic was developed to represent and resolute the problem. It was called ULS-AS-SRH.

Table 10: Planning horizon and solution method of the ULS-AS-SRP. To compare with other studies, go to section 2.5.1.

Planning horizon		Solution method		
SP	MP	Exact	Heuristics/Metaheuristics	Hybrid/Matheuristics
●			●	

4.1. Solution Methodology

This problem that will be presented is an extension of the VRP (Laporte et al., 2014), tailored to the *Unidade Local de Saúde Almada-Seixal* home healthcare context. While it shares key characteristics with the VRP, such as minimizing travel time and ensuring all destinations (patients) are visited, it introduces additional complexities like workload balancing and specific return time constraints for healthcare professionals.

The methodology implemented in the algorithm is grounded in several well-established algorithms and optimization techniques. The approach combines elements of greedy algorithms, exhaustive search, local search, and metaheuristics, particularly Simulated Annealing. This blend aims to effectively manage the assignment and routing of healthcare professionals, achieving a balance between computational feasibility and solution quality.

4.2. Overview of applied algorithms

The methodology integrates diverse algorithms and techniques into a coherent framework that effectively addresses the problem of scheduling and routing in a healthcare context. Each component—greedy algorithms, exhaustive search, local search, Simulated Annealing, and heuristic optimization—plays a critical role in the overall strategy, contributing to a solution that is both practical and efficient. By combining these approaches, the methodology balances the need for computational efficiency with the requirement for high-quality solutions, making it well-suited for real-world applications in healthcare service delivery. These methods are more appropriate for the type of problem being solved, where the solution space is discrete and the objective function is not differentiable.

4.2.1. Greedy Algorithms

Greedy algorithms are employed in the initial phase of the solution process, specifically for assigning patients to healthcare professionals. The core principle of greedy algorithms is to make the locally optimal choice at each step with the hope of finding a global optimum. In the context of this problem, a greedy approach quickly assigns patients to available doctors or nurses based on immediate, predefined criteria, such as proximity or workload capacity. This ensures that an initial feasible solution is generated with minimal computational effort, providing a solid foundation for further optimization.

4.2.2. Exhaustive Search

Within small, manageable subsets of the problem, the methodology incorporates exhaustive search to ensure optimality. Exhaustive search, or brute-force search, systematically explores all possible permutations of patient lists for a given healthcare professional. By evaluating each permutation, the algorithm guarantees that the best possible route is selected for these subsets. This method is computationally expensive and is thus limited to smaller subsets where the search space is sufficiently small to be explored fully.

4.2.3. Pathfinding Algorithm

The pathfinding algorithm employed is critical for calculating travel times between patient locations, thereby optimizing the routes taken by healthcare professionals. The algorithm utilizes the Haversine formula to calculate the shortest distance between two geographic coordinates. This distance is then used to compute travel times, which are critical for scheduling and routing decisions.

Equation 1 Haversine formula in this context[4].

$$d_{ij} = 2r\sin^{-1}\left(\sqrt{\sin^2\left(\frac{\phi_j - \phi_i}{2}\right) + \cos(\phi_i)\cos(\phi_j)\sin^2\left(\frac{\lambda_j - \lambda_i}{2}\right)}\right)$$

4.2.4. Local Search

Local search is a key component of the iterative improvement process. This method operates by exploring the immediate neighbourhood of the current solution. Local search is particularly effective for refining solutions because it allows the algorithm to gradually improve the solution by making small, incremental changes. However, the quality of the solution obtained and computing times often rely on the diversity and variety of the moves evaluated during each step of the heuristic process (Gendreau & Potvin, 2019).

[4] where d_{ij} is the distance between two locations (i and j), r represents the earth radius, ϕ the latitudes and λ the longitudes of the vertices.

4.2.5. Mechanisms to avoid local optima

The acceptance of worse solutions is governed by an exponential or algorithmic decay function. This function determines the probability of accepting a suboptimal move, which decreases as the algorithm progresses. The exponential decay ensures that, over time, the algorithm becomes more conservative in its acceptance of worse solutions, thereby honing in on the optimal or near-optimal solutions. This mechanism helps balance exploration and exploitation, allowing the algorithm to explore new areas of the solution space early on and refine promising solutions as it nears completion (Gendreau & Potvin, 2019; Kirkpatrick et al., 1983).

4.3. Requirements and assumptions

The following outlines the primary assumptions and hard constraints of this problem. Note that soft constraints were not allowed:

- A visit is only considered when a HHU vehicle goes to the patient's home. If the patient is auscultated at the hospital, it is assumed that a visit will not take place.
- Each visit is completed by a single vehicle (care worker), with no activity splitting permitted. The maximum number of routes corresponds to the number of available vehicles.
- The vehicle's (care worker's) travel speed is assumed to be 30 Km/h, with traffic and route conditions ignored (note: 30 Km/h is the urban speed limit in Portugal).
- Locations are represented by easting and northing coordinates for each postcode, and the Haversine or great-circle distance is assumed between locations.
- Each patient may require zero, one or more visits per day, but never more than one visit per shift.
- Each patient has an assigned responsible doctor and a specified location.
- The duration of care provided to each patient (the time the vehicle is stationary at the patient’s location) is known with low to moderate certainty. A triangular distribution is introduced in the algorithm based on averages published in the annual accounts report (Relatório e Contas, 2022; Table 9)

- Patients do not have predefined visit time windows; instead, a priority distribution of visits is implemented:
    - First priority-level is determined by disease complexity, where patients requiring more than one visit correspond to level 0, the highest priority, indicating these patients must be visited first.
    - Level 2 patients, who require staff to collect a sample for laboratory analysis, are visited last to avoid sample degradation (perishability).
    - By exclusion, level 1 accommodates all remaining patients.
- Care workers travel from the hospital to the patient's home and back to the hospital to deliver care.
- Caregiver's working shifts are exclusively dedicated exclusively to HaH care, though they perform other activities besides home care. Therefore, their capacity in the ULS-AS-SRP algorithm is considered to start at 9:00 AM and end at 3:30 PM (mandatory return time).
- While doctors are required to visit their pre-assigned patients, nurses are allocated to patients when doctors are unavailable.

Following the structure presented in section 2.5.1.2, the visit constraints in this algorithm include the use of a single depot (SD), ensuring continuity of care (CC) when the patient's responsible doctor is on shift, and skill constraints (Sk) when a doctor's presence is mandatory This is essential not only for continuity of care but also when admitting or discharging a new patient. Finally, precedence (Pr) constraints are integrated through a priority-based approach. For caregivers, working time (WT) is limited between 9:00 AM and 3:30 PM but can be adjusted for different shifts. The district area (D) is confined to the operational area of the HGO. Last but not least, workload balance (WB) is a core component of this algorithm and can be considered a constraint. Although not explicitly included in the objective function, the solution inherently aims to achieve workload balance among all workers.

4.4. Objective function

As discussed in section 2.5.1.3 it became clear that focusing solely on optimizing a single factor is impractical due to the complex nature of HHCRSP. As such, the objectives then included the caregivers' time of travel (handled within each route, using the Exhaustive Search mechanism), total working time and balancing workload.

Table 11 Objectives of the ULS-AS-SRP. To compare with other studies, go to section 2.5.1.

Route		Caregivers						Patients				
↓TT	↓TD	↓ W	↓ #C	↓ WT	↓ WaT	↑ WB	↓ O	↑ VTP	↑ P	↑ CC	↓ UV	↓ TWV
●				●		●						

In this note, two different objective functions were implemented. The first objective function is to minimize total working time.

Equation 2 First objective: minimize total working time.[5]

$$Minimize \sum_{k \in V} \left(\sum_{i \in P \cup \{H\}} \sum_{j \in P \cup \{H\}} T_{i,j} x_{i,j,k} + \sum_{i \in P \cup \{H\}} s_i \right)$$

Once a solution that minimizes the total working time is found, the next step is to minimize the second objective function: unbalanced workload among team members, which ensures that the cost is distributed as evenly as possible.

Equation 3 Second objective: minimize workload differences among caregivers.

$$Minimize \sum_{k \in V} \sigma_k$$

[5]Legend:

$T_{i,j}$ – Travel time between locations i and j; $x_{i,j,k}$ – Binary variable that equals 1 if vehicle k travels directly from location i to j; s_i – Procedure time required for patient i; V – Set of vehicles (doctors and nurses); P – Set of patients; H – Depot (hospital).

This approach allows customization and to explore different scenarios where not all objectives are of equal importance, besides it allows a clear direction in the optimization process by sequentially optimizing for each objective.

4.5. Initial assignment using Greedy Algorithms

The initial approach to solve the ULS-AS-SRP is to assign patients to the working professionals. It is handled in two phases:

a) Distribution to doctors

In the first phase of the patient assignment, each patient is assigned to their designated doctor based on predefined associations. This assignment is subject to the doctor' availability on the given day. The process works as follows:

i. Patient-Doctor matching: Each patient is matched with the doctor assigned to them, ensuring that each patient is directed to the physician responsible for their care.

ii. Doctor availability check: Only doctors who are scheduled to work on that day are considered for patient assignments. Patients whose designated doctors are unavailable will not be assigned during this phase.

iii. Optimization of doctor's route: Once all patients are assigned to their respective doctors, the route for each doctor is optimized. The optimization process involves:

  a. Priority-based scheduling: Patients are grouped and ordered according to their designated priority.

  b. Travel distance minimization: The route is further optimized by minimizing the total travel distance. An exhaustive path search is employed, evaluating all possible permutations of patient visits within each priority group to identify the sequence that minimizes travel time while maintaining priority constraints.

An illustrative example of the expected outcome is depicted in Figure 4.1.

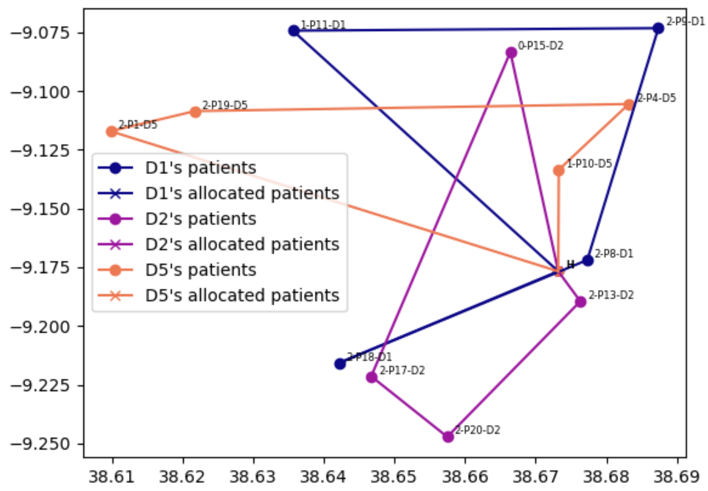


Figure 4.1 Initial distribution to doctors.[6]

b) Distribution to the remaining team members

Following the initial distribution to doctors, some patients may remain unassigned. This situation can arise due to the unavailability of the assigned doctors, limitations in capacity, or the need for specialized care provided by nurses. To address this, the team is expanded to include nurses, and the remaining patients are then systematically distributed among the available nurses and doctors. The subsequent allocation process is structured as follows:

i. Completion of the healthcare team: The initial team of doctors is supplemented by including nurses, with the expansion guided by the vehicle's capacity constraints.

ii. Allocation of unassigned patients: The remaining patients are then distributed among all the team members using a greedy approach:

   a. Assignment evaluation: Each unassigned patient's potential assignment to team members is evaluated based on cost. This evaluation mirrors the optimization process used during the initial route planning for doctors, focusing on priority-based scheduling and travel distance minimization. Moreover, for each team member, the optimal insertion position for the unassigned patient in the existing route is identified and recorded.

[6] Each dot in the figure represents a patient and is labelled in the format "Priority-Patient ID-Attendant".

b. The attendant with the minimal additional travel cost for including the patient is identified. The patient is subsequently added to this team member's route at the predetermined optimal position.

Subsequently, the previous distribution is updated to incorporate the new patient assignments, resulting in an initial feasible solution subject to further enhancement during the optimization process. This revised allocation is exemplified in Figure 4.2.

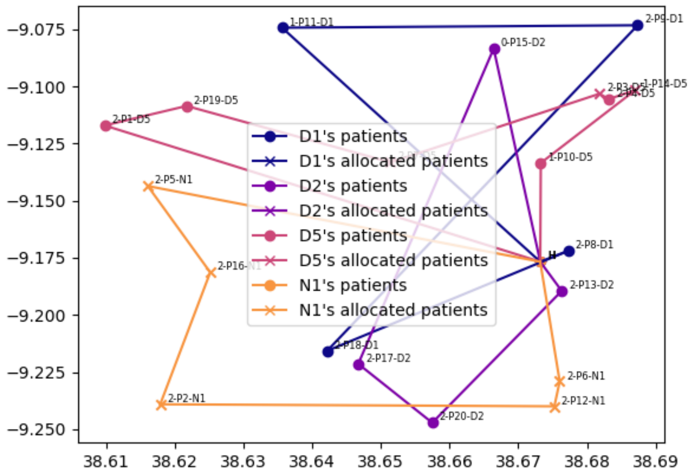


Figure 4.2 Initial distribution of all patients.[6]

Table 12 presents the pseudo-code that succinctly outlines the foundational approach of the initial assignment algorithm.

Table 12 Algorithm 1. Initial patient distribution.

```
Begin
  For each patient "p" in the list of patients
    Initialize empty lists for costs "fos" and positions "pos"
    For each attendant "a" in the team
      Add patient "p" to the attendant "a"
      Adjust the path of the attendant "a"
      Calculate the cost of the path and store in "fos"
      Remove patient "p" and store the position in "pos”
    End For
    Select the attendant with the minimum cost in "fos"
    Add patient "p" back to the selected attendant in the stored position from "pos"
  End For
End
```

4.6. Iterative Route Optimization with Local Search

After the initial patient assignment using the Greedy Algorithm, further optimization is necessary. An algorithm was developed specifically for the ULS-AS-SRP to ensure fast and high-quality solutions that surpass the current method used by *Unidade Local de Saúde Almada-Seixal.* This not only enhances visit efficiency but potentially prevents staff resistance to the new process. The algorithm focuses on minimizing total costs and the standard deviation of costs among team members through an iterative process. The approach balances workloads and optimizes routing, thereby improving overall operational efficiency (Table 13).

Table 13 Algorithm2. Iterative route improvement.

```
Begin
    Initialize factor, standard deviation list "std", number of iterations i, and initial objective function "fo"
    Save the initial configuration as the best configuration
    For each iteration "i" from 1 to the number of iterations
        Determine if double exchange should be attempted based on "factor"
        If a suitable pair of attendants for exchange is found
            Perform single or double exchange of patients between attendants
            Adjust the paths and recalculate the objective function "fo"
            If the new standard deviation is better, accept the exchange
            If the new configuration is better than the best so far, save it
        Else
            Undo the exchange and store the failed attempt
        End If
        Store the standard deviation in "std"
    End For
    Restore the best configuration
    Return the list "std" and the best configuration
End
```

The process encompasses several key phases:

a) Identification of Potential Route Improvements

Once the initial routes are generated, the algorithm systematically identifies the team member with the highest cost and the one with the lowest cost, while adhering to the pre-established constraints. These team members are the candidates for exchanging patients.

b) Patient exchange mechanisms

Periodically, based on a defined factor, the algorithm explores different exchange approaches in the selected iterations:

i. Single Exchange: The team member incurring the highest cost transfers a patient to the member with the lowest cost, to explore a more efficient route.

ii. Double Exchange: Each team member swaps one patient with another, enhancing the algorithm's efficiency by accelerating the exploration of the search space.

c) Route adjustment and recalculation

After an exchange, each route for both team members are recalculated using the path adjustment algorithm (the same as in section 4.5) and the new cost is computed. This ensures that the new sequence of visits is the most efficient possible within the new assignment.

i. Acceptance of Changes: The new configuration is accepted if the exchange resulted in a lower standard deviation of the costs among all team members (i.e. a more optimal solution) and becomes the new baseline for further optimization. Occasionally, to prevent the algorithm from converging prematurely to suboptimal local minima, non-optimal exchanges might be accepted probabilistically. Different approaches were tested and will be further explored in Computational Results section:

   a. Exponential decay: Inspired in simulated annealing (Afifi et al., 2013), to avoid local minima, this approach introduces a controlled level of randomness into the optimization process, enhancing the exploration of the solution space to occasionally accept worse solutions.

Equation 4 Exponential decay probability of accepting worse solutions.

$$P_{acceptance}(i) = P_0 \cdot e^{-\lambda}$$

   b. Logarithmic decay: This method balances the need for exploration in the early stages of the optimization process with the need for exploitation in the later stages, ultimately leading to a more robust and effective search for the optimal routing configuration.

Equation 5 Exponential logarithmic probability of accepting worse solutions.

$$P_{acceptance}(i)^{7} = \begin{cases} 1\ , if\ i\ mod\ 2^{log_2(i)} = 1 \\ 0\ otherwise \end{cases}$$

ii. Saving and restoring the best configuration: Throughout the iterations, the algorithm continuously monitors and records the best route configuration encountered (i.e., lowest overall cost and standard deviation).

At the end of the optimization process, the system restores the optimal configuration, displaying the sequence of patient visits. Figure 4.3 shows this optimal configuration for the provided example.

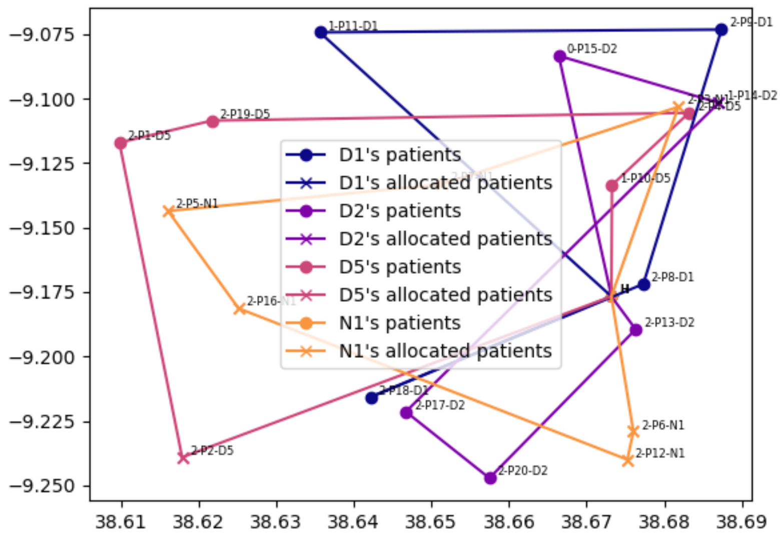


Figure 4.3 Optimal configuration after all the solutions generated by the optimization process.[6]

[7] Where i mod $2^{log_2(i)}$ is the remainder of dividing i by $2^{log_2(i)}$

5. COMPUTATIONAL RESULTS

This section presents the results of the computational experiments conducted to evaluate the performance of the developed scheduling and routing algorithm. The computational experiments were performed on a machine with an Apple M1 processor and 16GB of RAM, using Python 3.9 and associated libraries such as NumPy, Itertools, Math, Statistics and Random.

The algorithm was tested on a series of scenarios, each designed to reflect realistic conditions in a healthcare setting, including varying numbers of patients, geographical spread, and worker availability.

The lists of instances used were generated based on realistic parameters after collaboration with the HHU of *Unidade Local de Saúde Almada-Seixal* so that the data represents all possible scenarios, having in consideration the stochastic nature of HaH.

The algorithm efficiently and successfully distributed patients among available doctors and nurses, to a maximum of 28 patients per worker. It accounted for factors like patients' locations and visit priority, while optimizing routes to minimize travel time. As a result, each worker was able to complete their assigned visits and return in time for the meeting. Additionally, the algorithm maintained a balanced workload distribution across all team members, ensuring efficiency and fairness.

5.1. Results and discussion

The parameters listed in Table 14 were used in the algorithm across all instances tested.

Table 14 Values of the parameters used in the algorithm.

Parameter	Description	Value
i	Iteration	180
$factor$	Swaps factor	4
a	Initial probability value for exponential decay	0.5

It is important to note that, although the maximum iteration value (i) is set to 180, the algorithm does not necessarily run through all iterations (as it is explicit in Table 15). The logic of the algorithm halts its process once all available alternatives are explored, even if the maximum iteration count has not been reached.

Table 15 Computational experiments results.

Patient Number	Priority (Pr)	Doctor Number	Search Space Technique	Max iterations	Avg Computational Time [seconds]	Avg Total Travel Time [h]	Avg Total Working Time [h]	Avg SD [h]
20	All Pr1	0	Exp_log	49	1.65	3.34	17.74	0.1411
			Exp	65	1.77	3.2525	17.6525	0.0832
	Random parameters[8]		Exp_log	45	1.37	2.53	16.19	0.068
			Exp	61	2.18	2.755	16.415	0.0747
	All Pr1	1	Exp_log	61	2.25	3.14	17.54	0.0755
			Exp	81	2.29	3.14	17.54	0.0755
	Random parameters[8]		Exp_log	26	1.08	2.55	16.21	0.2095
			Exp	54	2.15	2.655	16.315	0.1839
	All Pr1	2	Exp_log	61	2.16	3.09	17.49	0.0806
			Exp	41	1.73	3.075	17.475	0.0829
	Random parameters[8]		Exp_log	31	1.34	2.61	16.27	0.2205
			Exp	55	1.46	2.6675	16.3275	0.2219
	All Pr1	3	Exp_log	105	3.18	3.26	17.66	0.0625
			Exp	53	2.11	3.3025	17.7025	0.0839
	Random parameters[8]		Exp_log	81	2.02	2.86	16.52	0.2061
			Exp	48	2.1	2.86	16.52	0.2061
	All Pr1	4	Exp_log	26	1.74	3.18	17.58	0.1754
			Exp	57	2.41	3.185	17.585	0.1934
	Random parameters[8]		Exp_log	47	2.12	2.9	16.56	0.2847
			Exp	47	2.04	2.88	16.54	0.2662
28	Random parameters[9]	0	Exp_log	57	2.57	4.15	23.59	0.0991
			Exp	109	3.2	4.0325	23.4725	0.1033525
		1	Exp_log	49	1.99	4.14	23.58	0.1843
			Exp	113	3.72	4.0825	23.5225	0.0603
		2	Exp_log	77	3.47	4.02	23.46	0.2151
			Exp	93	3.11	3.705	23.145	0.0996
		3	Exp_log	45	2.35	3.66	23.1	0.1369
			Exp	77	3.09	3.79	23.23	0.1074
		4	Exp_log	77	10.4	3.8	23.24	0.0374
			Exp	77	6.33	3.825	23.265	0.0598

[8] These random parameters resulted in 3 patients with priority 0 and 2 with priority 2.
[9] These random parameters resulted in 4 patients with priority 0 and 8 with priority 2.

The ULS-AS-SRP algorithm was tested using various search space techniques to avoid local optima, and with different numbers of attending doctors. In the first instance, 20 patients were considered, with none of them requiring multiple visits or sample collections. A second instance, also with 20 patients, was generated, but this time random parameters were applied based on a triangular distribution, reflecting real-world variability as suggested by the *Unidade Local de Saúde Almada-Seixal* healthcare professionals. In the third and final instance, the number of patients was increased to the maximum that the available resources at the HHU could handle, in a manner that allowed them to return before the afternoon meeting. This instance was designed to stress-test the system and evaluate the performance improvements from using the algorithm. Since this scenario is rare in practice, no tests were done assuming all patients had the same priority level.

The algorithms' performance was assessed using several performance metrics: (1) the number of iterations performed; (2) the average computational time to reach a solution; (3) the average total travel time for the four vehicles; (4) the average total working time for the four staff members, including travel and patient interactions; and (5) the average standard deviation, measuring the balance in workloads between the care workers.

5.1.1. Instance 1: 20 patients with uniform parameters

For the first instance, the results indicated that the exponential logarithmic search technique generally led to lower computational times compared to the exponential method. Travel times were also slightly better with the exponential logarithmic technique, though both techniques performed similarly overall. The difference in average total working time between the techniques was minimal, the maximum achieved between techniques was just over five minutes across all routes. In terms of workload balancing (as measured by standard deviation), the exponential technique performed marginally better, but the difference was not significant.

5.1.2. Instance 2: 20 patients with random parameters

In this instance, computational time remained low, with a maximum of just over two seconds. Travel time was again similar between both search techniques and across different doctor allocations. The exponential decay technique performed better in terms of total working time, with a maximum difference of 13.5 minutes across all routes. When looking at workload balancing, the results were mixed: the exponential technique performed better when 0 or 2 doctors were working, while the exponential logarithmic technique was superior with 1 or 4 doctors. For the scenario with 3 doctors (the most common case in the HHU's daily operations), both algorithms performed equally well.

5.1.3. Instance 3: 28 patients with random parameters

In the third and final instance, computational time increased with the number of doctors, reaching its peak when 4 working doctors were tested. This was particularly evident with the exponential logarithmic exploration of a broader search space. Surprisingly, the total travel time decreased as the number of doctors increased, with the exponential logarithmic technique outperforming the exponential method. In terms of total working time, the algorithm performs better when there are 3 doctors assigned to the shift, and again, the exponential logarithmic approach performed better in most of the tests. For workload balancing, the exponential logarithmic technique was more effective, though it struggled in the 3-doctor scenario.

In sum, across all three instances, computational time was consistently fast with no significant differences between the instances or scenarios. So, the most important note is that minimizing total working time can sometimes negatively affect workload balance. Overall, the algorithm successfully balances both objectives—minimizing total working time and standard deviation. The differences between the search techniques were minor, with the exponential logarithmic occasionally achieving slightly better results in terms of both travel and working times.

5.2. Algorithm complexity

When analysing the algorithm complexity, the focus is on its computational complexity, particularly the lower and upper bounds. These bounds offer insights into the best-case, worst-case, and expected performance under varying conditions.

The initial assignment employs a greedy approach, yielding an upper bound of $\mathcal{O}(n \times k)$, where n represents the number of patients and k the number of healthcare professionals. Conversely, the lower bound is $\mathcal{O}(n)$.

For visit ordering optimization within each professional's route, a brute-force approach is used, testing all possible configurations. This results in an upper bound of $\mathcal{O}(m!)$, where m denotes the number of patients assigned to a single staff member, making the algorithm computationally expensive as m increases. The lower bound in this case results in $\mathcal{O}(m)$.

The iterative route improvement algorithm applies a local search method, leading to an upper bound of $\mathcal{O}(n \times k \times i)$, where i is the number of iterations. The lower bound is $\mathcal{O}(n)$, assuming the initial local search for each patient identifies the optimal assignment.

Thus, the overall algorithm has an upper bound complexity of $\mathcal{O}(n \times k \times i + m!)$ and a lower bound of $\mathcal{O}(n)$, assuming the greedy approach approximates the optimal solution. The factorial complexity of the permutation search significantly contributes to the upper bound, potentially slowing the algorithm for large patient-to-professional ratios. However, in the specific problem analyzed, the algorithm performs efficiently with heuristics, providing a good solution in a short computational time.

6. ACKNOWLEDGEMENTS AND FUTURE RESEARCH DIRECTIONS

The proposed scheduling and routing system for the Home Healthcare Unit at *Unidade Local de Saúde Almada-Seixal* is designed to deliver optimized visit schedules while reducing route-associated costs. This system not only seeks to manage staff workload and promote fairness but also enhances patient satisfaction by providing an approximate schedule for visits. By automating the planning process, healthcare professionals can focus on delivering care, the core value of the service, leaving the complexities of scheduling and route planning to the system.

A significant advantage of this system is the visualization of optimized routes, offering a clear and organized overview of planned visits, start times, and end times. As noted by Salvendy (2001), structured schedules and visible timelines encourage adherence, improving both workflow and employee engagement. The visibility of assignments ensures that each healthcare professional is aware of their tasks and can follow the most efficient route, leading to improved operational efficiency. A crass limitation of the algorithm is that it doesn't take into account the requirement that if a patient is discharged requires a visit by a doctor.

To further enhance the system, future developments should focus on integrating the doctor requirement of discharged patients. Additionally, incorporating robust planning techniques and rescheduling algorithms would be essential for managing uncertainties, such as stochastic demand, unanticipated schedule changes, and factors affecting staff satisfaction, including break times. Advanced heuristics, such as Large Neighborhood Search or hybrid approaches combining exact and heuristic methods, could significantly improve the quality of the solutions. Moreover, incorporating machine learning algorithms to dynamically predict patient needs presents a promising avenue for future research. Predictive analytics could anticipate patient demand patterns, allowing for more proactive and efficient adjustments to the schedule.

These improvements will not only enhance the system's performance but also elevate the quality of home healthcare services. Ensuring that patient care remains efficient and responsive to changing needs will reinforce the hospital's commitment to excellence in healthcare delivery.

As efforts are being made to expand HaH programs in Portugal, optimizing daily operations through such systems will represent a considerable improvement over the existing manual processes. This transformation is essential to meet the increasing demand for home healthcare, ensuring both operational efficiency and high-quality patient care.

7. CONCLUSIONS

The implementation of Hospital at Home (HaH) programs provides a pivotal opportunity for hospitals to enhance operational efficiency, reduce bed occupancy, and manage resources more effectively. By shifting care to home environments, hospitals can focus on more critically ill patients, reduce the risks associated with hospital-acquired infections, and lower costs related to extended stays. HaH contributes to improved patient outcomes, faster recovery times, and increased patient satisfaction, while reducing readmissions and alleviating pressure on hospital resources. This model is particularly beneficial for managing acute, stable conditions that require short-term treatment, optimizing the utilization of medical staff, and enhancing telemedicine utilization to expand the reach of healthcare providers.

Furthermore, HaH offers hospitals the flexibility to handle surges in patient volume and manage elective procedures without delays caused by emergency overflows. It allows better resource allocation and optimizes the use of hospital-based medical devices. In parallel, the development of the scheduling and routing system for HaH at *Unidade Local de Saúde Almada-Seixal* marks a significant improvement over the current manual processes. By automating visit scheduling and staff routing, the system not only saves time but also enhances patient-centered care and staff well-being by ensuring equitable workload distribution. The heuristic-driven approach optimizes daily operations, balances staff workloads, and provides efficient visit sequences. As a result, the *Unidade Local de Saúde Almada-Seixal* —an improvement from the current capacity of 20— using the same resources. This proves that the ULS-AS-SRP approach marks a substantial advancement in managing the HaH resources at *Unidade Local de Saúde Almada-Seixal.*

Summing up, the integration of HaH programs and advanced scheduling systems results in improved operational flexibility, optimized healthcare delivery, and better management of healthcare professionals, aligning with the growing demand for home-based care.

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