Distributed Scheduling based on MAS: a Swarm Approach for Collaborative Optimization

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UMinho | 2023

Universidade do Minho
Escola de Engenharia

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April, 2023

REPÚBLICA PORTUGUESA
CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR
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PORTUGAL 2020
UNIÃO EUROPEIA
Fundo Social Europeu
NORTE2020

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Escola de Engenharia

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Distributed Scheduling based on Multi-agent System: a Swarm Approach for Collaborative Optimization

Doctoral Thesis
Doctoral Program in Industrial and Systems Engineering

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April, 2023

This document was created with the (pdf/Xe/Lua)LaTeX processor and the NOVAthesis template (v7.0.0) [136].

Acknowledgments

This PhD was a solitary journey into scientific discovery. Yet, at the same time, there were several highs and lows, however, it was a magnificent window of opportunity to expand my knowledge and to learn from incredible people. In addition, that work was not the result of my solitary commitment but the result of the support of many people and institutions. Here is my opportunity to acknowledge all people I have been involved with during the past years. I want to take this moment to dedicate this work to my beloved grandparents.

I would like to offer heartfelt thanks to my advisors and express my gratitude to the people who supported and inspired me to embark on my PhD development, both professionally and personally. First of all, my supervisor, Prof.ª Ana Maria A. C. Rocha, for their careful guidance and rigorous oversight of this thesis, constantly motivated me to perform to my maximum ability. I am also grateful for the precious advice, confidence in my work, and support whenever necessary. Second to my co-supervisor, Prof.ª Ana I. Pereira, for the opportunity, encouragement, and belief in my capacity to accomplish it. I am very grateful for her permanent support but mainly patience and perseverance, as well as for all the knowledge and experience provided over these years. I would also like to thank her for her friendship and magnificent ability to listen in those not so good moments. Third my other co-supervisor, Prof. Paulo Leitão, for the opportunity and example of professionalism, for strengthening my foundations in multi-agent systems, for his scientific guidance and for having an important role in the design and development of this work.

I also thank all the professors and colleagues from the University of Minho and Polytechnic Institute of Bragança, who contributed directly or indirectly to the realization of this work, and to everyone who supported me and stood by my side during this journey. I would like to thank my workmates from the CeDRI and ALGORITMI research centers, who accompanied me on this research journey, especially Beatriz and Filipe.

I would also like to note a special thanks to the Portuguese Foundation for Science and Technology (FCT) for the financial support to complete this work successfully (doctoral scholarship SFRH/BD/143745/2019).

Likewise, I would like to thank all my friends, without exception, for their constant friendship over many good years. A special thanks to Helena, not only for your help without expecting anything in exchange but above all for your availability.

I deeply appreciate and thank Joana for all the love, understanding, motivation and unconditional support in this adventure. Por ti tudo!

Finally and not least, I wish to express my love and my gratitude to my parents and sister for their constant support, education, encouragement, and never-ending patience, without them this work would never be possible.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Abstract

Distributed Scheduling based on Multi-agent System: a Swarm Approach for Collaborative Optimization

Countries worldwide are increasingly dealing with an aging population, especially in the interior regions of Portugal. Thus, given the difficulty that hospitals have in managing their logistics, there is a growing demand for Home Health Care (HHC) services, which have become extremely important in the daily lives of many people, who regularly receive social support and/or health care. However, the strategic and operational planning of HHC is facing problems, in addition to a high level of uncertainty, needing to incorporate digital technologies to meet the growing demand for real-time processes and operations, which is a challenging task. Currently, HHC scheduling and routing planning are often performed manually (without computational support), leading to inefficient solutions and increased costs. To cope with this, the ability to effectively and efficiently investigate, discuss and innovate in decision support systems is crucial, since manual planning or methods are generally centralized and deterministic.

This thesis aims to contribute to these complex and priority challenges to the lives of care workers and patients can be mitigated through the use of intelligent models and methods, which, when coordinated, can generate optimized and distributed solutions. In this work, the design and development of a disruptive and decentralized architecture were proposed, which integrates the optimization and Multi-agent System (MAS) modules. The architecture is supported by a database and a control interface, which served as a guideline to digitalize and produce scheduling and route plans with real-time flexibility and optimized responses, especially in the case of unexpected events. In this sense, the proposed architecture, based on the distribution of control functions over a swarm network of decision-making entities, was implemented and validated. The results showed that its performance was superior by combining the best of models and methods, with emphasis on MAS and optimization methods. On one hand, MAS guarantees a fast response to uncertainty conditions, while the optimization module achieves optimal solutions, i.e., a hybrid collaboration between these modules guarantees autonomy, robustness and responsiveness in domains with emerging needs. Finally, the Dynamic and Optimized Collaborative System for Routes (DOCtoR) prototype was proposed as an innovative system that integrates cloud tools, monitoring, optimization and MAS skills to support home care visits, meeting the operational needs faced by a real scenario in the Obra Social Padre Miguel (OSPM), an Private Institution of Social Solidarity (IPSS) in Bragança, Portugal. The platform focuses on modernizing and digitalizing the services performed by OSPM and creating a smart system for data exchange, scheduling and optimized management of routes, resources planning, and users. In this way, it will be possible to coordinate more effective responses to social, health and safety needs, in a dynamic and personalized way for all stakeholders.

Keywords: Home Health Care, Scheduling, Routing, Optimization, Multi-agent Systems

Resumo

Escalonamento distribuído baseado num sistema multiagente: uma abordagem para otimização colaborativa

Os países em todo o mundo estão a lidar cada vez mais com o envelhecimento da população, especialmente nas regiões do interior de Portugal. Assim, dada a dificuldade dos hospitais gerirem a sua logística, existe uma maior procura pelos cuidados de saúde domiciliários (HHC), que se tornaram de extrema importância no quotidiano de muitas pessoas. No entanto, o planeamento do HHC está a enfrentar problemas, que para além de um elevado nível de incerteza, necessita de incorporar tecnologias digitais para responder à crescente procura de processos e operações em tempo real, o que constitui uma tarefa desafiante. Atualmente, o escalonamento e o planeamento de rotas do HHC são frequentemente realizados manualmente, o que conduz a soluções ineficientes e a custos acrescidos. Para fazer face a esta situação, a capacidade de investigar e inovar de forma eficaz e eficiente em sistemas de apoio à decisão é crucial, uma vez que os métodos usados são geralmente centralizados e determinísticos.

Esta tese visa contribuir para que estes desafios complexos e prioritários para a vida dos cuidadores e dos pacientes, possam ser mitigados através do uso de métodos inteligentes, que quando coordenados, possam gerar soluções otimizadas e distribuídas. Neste trabalho, foi proposto o desenvolvimento de uma arquitetura disruptiva e descentralizada, que integra um módulo de otimização e um sistema multiagente (MAS). A arquitetura é suportada por uma base de dados e uma interface, que servem como diretriz para digitalizar e produzir escalonamentos e rotas com flexibilidade e respostas otimizadas, especialmente no caso de eventos inesperados. Neste sentido, foi proposta, implementada e validada uma arquitetura baseada na distribuição de funções sobre uma rede de entidades com tomada de decisão. Os resultados mostraram que o seu desempenho foi superior ao combinar o melhor dos modelos e métodos, com destaque para o MAS e algoritmos de otimização. Por um lado, o MAS garante uma resposta rápida a condições de incerteza, enquanto o módulo de otimização consegue soluções ótimas, ou seja, uma colaboração híbrida entre estes módulos, garante autonomia, robustez e capacidade de resposta em domínios com necessidades emergentes. Por fim, foi proposto o protótipo DOCtoR, que é um sistema inovador que integra ferramentas *cloud*, monitorização, otimização e competências de um MAS para apoiar as visitas domiciliárias, atendendo às necessidades operacionais de um cenário real na OSPM, uma IPSS de Bragança, Portugal. A plataforma tem como foco a modernização e digitalização dos serviços prestados pela OSPM e a criação de um sistema inteligente para troca de dados, escalonamento e gestão otimizada de rotas, recursos e utilizadores. Desta forma, será possível coordenar respostas mais eficazes às necessidades sociais, de saúde e segurança, de uma forma mais dinâmica e personalizada para todos os intervenientes.

Palavras-chave: Cuidados de Saúde Domiciliários, Escalonamento, Rotas, Otimização, Sistemas Multiagente

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Glossary

mHealth *mHealth* (abbreviation for mobile health) is a general term for the use of mobile devices, tablets, computers and other wireless technology in health care. The most common application of *mHealth* is the use of mobile devices to educate consumers about preventive healthcare services [93, 1]. *(pp. 31, 67, 101, 122, 125, 126, 129)*

NP-Hard The complexity class of decision problems that are intrinsically harder than those that can be solved by a nondeterministic Turing machine in polynomial time. When a decision version of a combinatorial optimization problem is proved to belong to the class of NP-complete problems, then the optimization version is NP-hard [36]. *(pp. 1, 2)*

Acronyms

ACL Agent Communication Language *(pp. 52, 109)*
AI Artificial Intelligence *(pp. 1, 3, 7, 9, 22, 31, 33, 50, 54, 63, 87, 128, 151)*
API Application Programming Interface *(pp. 36, 53, 61–64, 106, 108, 109, 114, 120, 126, 156)*

BB Branch and Bound *(pp. 43, 63, 71, 74, 93, 96)*

CG Column Generation *(pp. 24, 43, 44, 54, 69, 72, 74, 75, 96, 128)*
CNP Contract-Net Protocol *(pp. 52, 63, 84–86, 91, 98, 109)*

DOCtoR Dynamic and Optimized Collaborative System for Routes *(pp. v, vi, 101, 104–111, 113–115, 118–121, 123–128, 154, 156)*

EU European Union *(p. 4)*

FIPA Foundation of Intelligent Physical Agents *(pp. 52–54, 86)*
FIPA-ACL Foundation for Intelligent Physical Agents - Agent Communication Language *(p. 52)*

GA Genetic Algorithm *(pp. 24, 45, 46, 49, 62, 75–79, 81, 87, 89–93, 96, 97, 109)*
GUI Graphical User Interface *(pp. 53, 54)*

HHC Home Health Care *(pp. v, vi, x, 2–15, 17–19, 21, 22, 24–28, 30–37, 40, 42, 51, 55, 56, 58, 59, 61, 62, 64, 65, 67, 75, 76, 79, 81, 83–90, 94, 96–99, 101, 102, 107, 109, 119, 122–125, 127, 128, 147)*
HHCSRP Home Health Care Scheduling and Routing Problem *(pp. 7, 12, 19–22, 24–26, 33, 35, 40, 42, 45, 55, 62, 68, 69, 75, 76, 79, 81, 99, 100, 110, 124–127)*

ICT Information and Communications Technology *(pp. 59–61, 87, 121, 122, 124, 125, 128)*
IPSS Private Institution of Social Solidarity *(pp. v, vi, 4, 7, 13, 65, 66, 100, 101, 104, 105, 107, 118, 119, 121, 154)*
IT Information Technologies *(pp. 6, 12)*

JADE JAVA Agent DEvelopment Framework *(pp. 53, 54, 63, 83, 86, 109, 114, 116, 156)*

KPI Key Performance Indicator *(pp. 16, 17, 95, 98, 99, 117–119)*

KQML Knowledge Query and Manipulation Language *(p. 52)*

LTCNN Long-term Care National Network *(pp. 4, 17)*

MAS Multi-agent System *(pp. v, vi, 2, 7–9, 12, 19, 24, 26, 33, 50–56, 59, 60, 62, 63, 66, 67, 83–87, 89–91, 94, 95, 97–101, 109, 114–116, 118, 121–124, 126–128, 151, 156)*

MILP Mixed Integer Linear Programming *(pp. 24, 43, 69, 70, 74, 93, 94, 96)*

ML Machine Learning *(p. 3)*

MOO Multi-objective Optimization *(pp. 48, 49, 78, 81, 109)*

OECD Organization for Economic Cooperation and Development *(pp. 17, 18)*

OR Operations Research *(pp. 5, 7, 19, 22, 31, 33, 54, 87, 106)*

OSPM Obra Social Padre Miguel *(pp. v, vi, 13, 101–103, 105, 107, 111, 113–121, 123, 125–127)*

PSO Particle Swarm Optimization *(pp. 24, 45–47, 62, 75–77, 88, 89, 96, 109)*

PVRP Periodic Vehicle Routing Problem *(pp. 69, 70, 72, 74, 94, 96)*

RMP Restricted Master Problem *(pp. 44, 72, 73)*

TCP/IP Transmission Control Protocol/Internet Protocol *(pp. 120, 156)*

VRP Vehicle Routing Problem *(pp. 16, 19–22, 26, 31, 36, 106)*

WoS Web Of Science *(pp. 22, 23, 27, 28, 149)*

1

Introduction

"Engineers like to solve problems. If there are no problems handily available, they will create their own problems." - Scott Adams.

In today's manufacturing, healthcare and service operations management sectors, sequencing, planning, scheduling and routing are critical decision-making processes [142]. The scheduling of customer service and the routing of service vehicles are at the heart of many service operations. People often use the word "scheduling", although they are not always clear about concept. Scheduling and/or planning is a crucial but extremely difficult process in any industry or service management. The purpose of scheduling is to plan and allocate resources (employees, vehicles, etc) among tasks over time in order to: 1) maximize/minimize one or more objectives, such as makespan times and/or costs; 2) decrease task runtime; 3) workloads; 4) make workforce available; and finally 5) better deal with the priorities of the problem [129, 142]. On the other hand, routing is also not ab easy process, since it is difficult to map out specific routes that vehicles and drivers will take to accomplish these tasks (e.g., deliveries). Basically, route planning is the process of to get the proper scheduling allocations and mapping out precise (and optimal) routes for delivery drivers or service professionals, seeking to optimize factors such as capacity constraints, travel time and distances or transportation costs [162].

This type of decision-making process plays a vital role in many industries, manufacturing or health services, involving NP-Hard problems, such as scheduling and routing [163]. The ongoing research, digitalization and modernization of industrial processes, health scheduling, social assistance, and other service delivery environments allow the achievement of higher levels of decision-making, adaptations, and flexibility in systems that must cope with a large and growing demand and a market that is constantly changing due to mass customization and high-quality services or products. It focuses primarily on the application of optimization algorithms, mathematical formulations to streamline processes, cloud computing, and Artificial Intelligence (AI) technologies. The development of smart processes and products to handle data and time-sensitive requirements has proven to be heavily based on all these intelligent and evolutionary mechanisms, which have demonstrated to be fundamental enablers of scheduling applications. In this regard, offering scheduling solutions combines the use of digital technologies, optimization techniques and smart strategies. Mixing these approaches would increase the ability to effectively support distributed, decentralized, fast and optimized solutions.

This work aims to address the challenges associated with the design and development of distributed, optimized, and intelligent mechanisms that, through a computational system, allow the definition of models and methods, guidelines, and help in the automation of scheduling and routing processes to assist the decision-maker in the Home

Health Care (HHC) sector. This project is motivated by the significance of the HHC service and the corresponding need for improvements in the service process, from scheduling to routing, its strategic goals, requirements and operational constraints. Based on that, this thesis proposes a smart conceptual framework, implemented and codified in a web/mobile application, that defines a joint architecture with integrated optimization and MAS modules, a database, and a general dashboard to monitor, connect the integrated modules, distribute the data, and digitalize the solutions.

The remaining sections of this chapter are organized as follows:

- Section 1.1 – the background provides the context of the study and establishes its significance. It introduces the research topic and leads the readers to the knowledge gaps that were left unaddressed. It also briefly contextualizes the key technologies that have enabled the development of scheduling solutions, considering the importance and challenges associated with optimization techniques, smart solutions, supporting decision-making and decentralizing data. The HHC problem is defined and prioritized for solution approval.

- Section 1.2 – the objectives and research questions discusses the main goals of this work, together with the underlying assumptions, working hypotheses, and research questions used to achieve them.

- Section 1.3 - the scientific research methodology explains the research strategy employed to drive this work.

- Section 1.4 – the document organization outlines how the chapters that discuss the research, design, development and experimentation have been included and organized.

- Section 1.5 – a brief summary of the dissemination results of the work, as well as some notes on awards and merits received in the scope of the thesis research.

1.1 Problem Background

According to the literature, scheduling problems are NP-Hard, meaning they are complex and challenging to solve [163]. When planning, many different factors must be considered, and sometimes there are unforeseen events that require a timely response. In addition to being time-consuming, ineffective, complex and robust, scheduling solutions are frequently disregarded in real-world scenarios, where they are sometimes carried out manually, in data sheets, or in simple or limited software programs. The current dynamic scenarios in various sectors of society and the multiple inputs/outputs of data, have resulted in the growing demand for highly customized products and/or services with multiple variants, forcing organizations to quickly embrace new market opportunities and thrive in a highly competitive world [2].

An effective lever for generating value for companies and society is to optimize the functionality and flexibility of services and industrial systems. In this sense, the optimization phase is one of the key procedures that enables the guarantee of higher productivity while respecting a variety of constraints, including quality standards, process safety, environmental impact and other operational or financial issues. These constraints (limitations) are related to the types of products and services offered and the environments in which they are produced. The main goal of most organizations is to ensure that the use of plants, activities, and other logistical resources is optimized to respond quickly to market changes and disruptions. According to this perspective, industrial and/or service systems should be as flexible as possible to be able to allocate resources, reorganize operations, and distribute capacities, among others [158].

To accomplish this, it is crucial to create a well-organized schedule with specific instructions for each task to be performed, including where and when it should be done. This is true for sectors including transportation services [49], staff distribution [73], manufacturing processes [131], and/or logistics related to HHC [86].

Some of the challenging topics covered in this problem and applied to different sectors may include:

- Mathematical optimization and algorithms based on approximation methods using heuristics and meta-heuristics to solve planning and scheduling problems in engineering, manufacturing, and healthcare systems.
- Exact algorithms (such as branch-and-bound, etc.) for scheduling and planning issues.
- Applications for planning and scheduling (such as timetabling, network routing, crew scheduling, production scheduling, and project scheduling under resource constraints).
- Approaches to smart optimization for intelligent systems (Artificial Intelligence, AI, and more recently, Machine Learning, Machine Learning (ML)).
- Data digitalization and analytics (manufacturing, and/or HHC services, etc).

Considering these different topics, it is important to mention that the focus of the work will be to boost the healthcare sector, namely in HHC management contexts and promote innovation and intelligent scheduling solutions in this sector. The HHC service has more and more adherents and, in this segment, more needs and innovation are requested.

The population has been aging in developed countries during the last few decades due to a broad increase in life expectancy and a significant decrease in the fertility rates of younger generations. The World Health Organization predicted in 2019 that by 2030, there would be a 56% increase in the adult population aged 60 and over, from 962 million to 1.4 billion, rising to more than 2.1 billion by 2050 [157].

The demand for home health care is increasing in parallel with the demand for long-term care. People often develop difficulties as they age, which are usually caused by non-communicable diseases. Alzheimer's disease is an example of a illness in the category of dementia that affects memory in older people in the early stages and can progress to cause disorientation, behavioral problems, and a disregard for self-care, among other problems. The inability to complete specific tasks results in a loss of independence and the requirement for care provision.

Regarding HHC services, in their general scope, they are generally based on any type of care service provided to the patient in his own home, namely assistance with daily living, household and nursing activities [96]. Healthcare professionals, such as nurses, physicians, social workers, caregivers, etc., are increasingly needed to provide care to patients at home as the population ages [70]. HHC has several advantages, such as reducing total care expenses because patients receive their care at home and do not require 24-hour monitoring by medical staff and order to free up hospital beds for those who genuinely need them [54, 70]. In the past 20 years, home care systems have been implemented in numerous nations to increase access to healthcare services [102]. The Bureau of Labor Statistics predicts that "employment of home health and personal care aides is projected to grow by 33% between 2020 and 2030" [44]. As demand for HHC increases, health care providers will need to find ways to keep up. Furthermore, there are some factors that will soon contribute to the growing importance of HHC. These include, among other reasons, improvements in medical/digital technology and the preference of patients to spend as much time as possible at home [76]. In addition, modeling the preferences of patients and healthcare professional improves service quality, satisfaction, and work-life balance. Thus, home health/social care has an essential impact on the quality of life of its users and allows them to keep living in their homes and with their family, rather than moving into nursing homes or similar facilities [100].

In many countries, the HHC is funded by public authorities, such as the example of Portugal [56]. This work focuses more on formal care, leaving informal care (more personal or familiar) somewhat aside, particularly as the latter is currently in decline. Thus, formal care can be provided by public or private entities, however, this work sought to contribute to the public domain. Formal care is normally the responsibility of the Portuguese National Health Service (hospitals and health centers - being the HHC service responsible for the Long-term Care National Network (LTCNN) and also social security entities (called IPSS). LTCNN is an organizational model created by the Portuguese Ministry of Labor and Social Solidarity and Health, formed by a set of public and private institutions. Its goal is to provide health care and social support in a continuous and integrated way to people who, regardless of age, are in a situation of dependence. The associated care is focused on the overall recovery of the person, promoting their autonomy and improving their health, in the context of the dependency situation in which they find themselves [135]. Social Security provides benefits in kind (personal care and home care) and in cash in order to assure long-term care in Portugal. The institutions that provide the actual care are the IPSS, which are partially financed by the state [95]. Various services and facilities are currently provided for the elderly, including day care facilities, home care, and nursing homes (palliative and long-term care) for those who are extremely dependent. However, the growing demand for these services has demonstrated that these organizations cannot support all the requests to which they are subject.

As a result, the lack of funding for IPSS causes significant financial difficulties, drastically reducing the number of patients eligible for care and the number of people who can enroll in institutions. For this reason, good management practices, especially in finding solutions for scheduling and routing HHC, must be implemented immediately [105].

In Portugal, the imbalances in the distribution of population throughout the territory are accentuated, with a greater concentration on the coast and close to the capital. In addition, the phenomenon of population aging has also worsened in recent years, with a significant increase in the elderly population and a decrease in the young population: in 2021 there were already 182 elderly people for every 100 young people [187]. In fact, Portugal is the fastest aging country in the European Union (EU). These indicators can be verified in Figure 1, where the vertical axis on the left represents the ratio, while the vertical axis on the right showcases the respective proportion. The representation of the indicators over the years in Portugal is shown on the lower horizontal axis.

According to the general information obtained through Census, the statistical data demonstrates the constant growth of aging indicators such as: the aging index, total dependency rate, old age dependency ratio, and longevity index. In addition, the old age dependency ratio has increased considerably (35% in December 2021), reaching the highest percentage in the country's history and the fourth place in the table of the highest dependency rates at the EU level. On the other hand, the young-age dependency ratio contrasts with the previous ones, as its decline has been accentuated.

Another important fact is that, compared to the Census 2011, there has been an increase in the number of people who live alone and/or isolated, in a situation of vulnerability due to their physical or psychological condition or due to other condition that can compromise their safety. On the other hand, the average size of private households has increased, especially in inland regions with low population density (2021 edition of the "Senior Census" Operation).

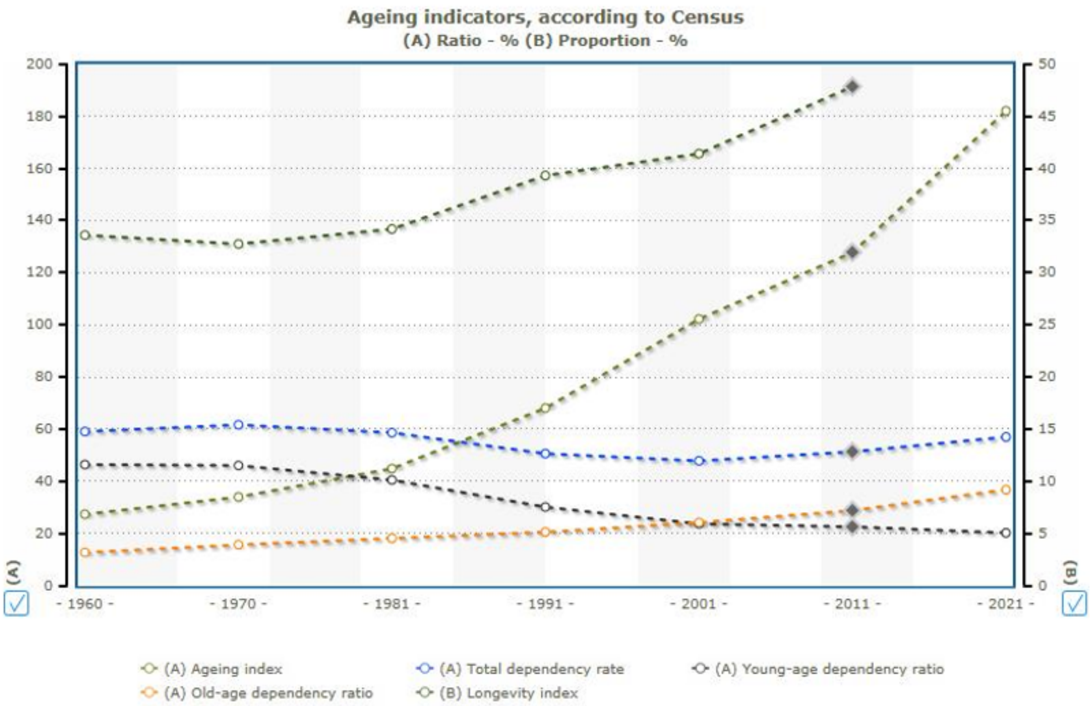

Figure 1: Statistical indicators on indices of aging, according to the 2021 Census. Sources: PORDATA [167].

For example, the district of Bragança is a major focus of the operation due to its high vulnerability. In this way, social, health and community intervention are increasingly urgent, while the adoption of home visits is clearly necessary. This relates with the provision of care and collaborative practices with the elderly and/or in situations of vulnerability.

In this sense, organizations or entities that provide HHC services aim to assign health professionals, caregivers and/or nurses to visit patients at their homes and provide essential services such as medical examinations, wound care, therapy, and social services [151]. For example, patients who receive medical care at home have a substantially reduced risk of contracting COVID-19 than those who attend a hospital, especially during a pandemic such as that one. Due to this, nowadays it is expected that the demand for HHC services could increase exponentially. Home care scheduling will become even more important, as it will allow care teams to support more patients without massively increasing their staffing numbers.

Therefore, the daily planning and management of home care is more complicated than hospital and/or residential care due to the dispersed geographical location among patients [107]. The operational management that needs to be determined and assigned is not only the duty plan of health professionals (nurses or caregivers), but also the driving routes. Many conditions must be met during the planning process. With more patients, workers, restrictions, requirements and regulations, the complexity increases, making the task more challenging. Operations Research (OR) quantitative approaches have the ability to ensure effective and sustainable planning as well as to consider several requirements at the same time.

This growing elderly population increases the demand for healthcare and challenges the Portuguese HHC system to innovate to control cost, quality and efficiency. One area of innovation is the transformation of HHC into a care organizing closer to the patient, in the community, or at home. Care delivered at home can range from monitoring a patient at distance using digital technology, such as monitoring assignment routes, health professional schedules, and the consequent data management, as well as operational planning of all resources. In the procedure for providing treatment to patients at home, several decisions must be made, including the number of patients to be treated, locations, time and distance matrix, the number of health professionals or caregivers needed to treat the patients, the orders for treating patients, the assignment of nurses to patients, and the timing of when a patient is treated by a particular technician. These decisions mirror those made in "normal" HHC situations, such as when a patient receives residential home care services such as washing or bathing.

According to some authors, there are three operational levels in healthcare planning: strategic planning, tactical planning, and online/offline operational planning. The following decisions must be made in HHC [112]:

- Strategic planning: policies, service, districting, capacity sizing;
- Tactical planning: capacity allocation admission control, staff shift scheduling;
- Offline/Online Operational planning: assessment and intake, staff assignment and visit scheduling, emergency, adjustment or rescheduling, routing.

Thus, HHC decision makers and managers are inclined to improve planning strategies, such as digitalizing procedures, optimizing processes and enabling the system for intelligent responses to fulfill the ever-increasing demand. Designing routes and managing working hours for health care personnel is a difficulty with HHC routing and scheduling, which directly affects planning operations (sequencing, combinations, allocation processes, etc.).

In addition to all that has been mentioned, unexpected events can change the original caregivers schedule by speeding up or postponing some daytime visits:

- Due to the patient's condition on that particular day, a specific treatment may have taken longer than anticipated;
- Additionally, there may have been traffic jams or road incidents that caused the session to start and end later than planned.

Daily schedules can be severely disrupted by being late. A shorter than anticipated appointment could also have an impact on the schedule, providing the caregiver with the flexibility to rearrange patient appointments to maintain the best routing. Therefore, in case of delays or opportunities to provide services earlier, it is imperative to update the routing and scheduling of visits. Depending on the scheduling time horizon, these issues can be categorized as single-period (such as a single day) optimization problems, multi-period (such as a week or a month) optimization problems, multi-objective optimization problems, among others.

Today, HHC providers can operate more efficiently (with computational support) and care for more patients if they use tools and technology to optimize service delivery and help with more dynamic scheduling and routing solutions [86]. The driving force behind this is the constantly changing market and customer demands, which, in addition to creating new business challenges, further enhance the already present complexity of operations that organizations face in real environments. Beyond these assumptions, the disruption in the healthcare sector has been caused by the arrival of new paradigms, new technologies and processes, as well as the cheaper development of Information Technologies (IT) infrastructure and the potential for digitalization. However, organizations have moved from a centralized (with one central authority) to a more decentralized architecture in many areas of decision-making, including collaborative scheduling solutions for HHC, in order to remain competitive in today's rapidly evolving business environment. To accomplish this and taking into account the information described here, a partnership with a Portuguese solidarity institution was established, so that real-life instances can be obtained to test the models, algorithms, and platforms. The institution at stake is Obra Social Padre Miguel - IPSS, located in Bragança, Portugal.

1.2 Objectives and Research Questions

This research project primarily covers the operational planning phases, as it focuses on optimizing the routing, and scheduling for both offline and online support.

Aiming to address the challenge of distributed scheduling and routing decisions / solutions, this thesis focuses on the design and development of optimized algorithms, namely exact and (meta)heuristic methods and MAS to be implemented in conjunction with HHC services, which can be used individually or in combination to address the different requirements and constraints of the problem, particularly at the strategic, tactical and operational levels.

In this sense, the main objective of the work is to propose a computational infrastructure (based on several approaches) to support the design and development of distributed and intelligent scheduling solutions to be deployed on a customized and dedicated platform (ranging from a web device in the cloud to a mobile app) for a home healthcare service. They should also be equipped with various optimization strategies, data analysis skills and collaboration tools to share information, fulfill their responsibility, and support the dynamic system adaptation. This work aims to design a distributed scheduling system that combines different techniques and intelligent methods. For this, it will be necessary to take advantage of properties and the inherent features of (meta-)heuristic algorithms, combined with the MAS approach and digitalization technologies that can provide data storage, local processing, communication protocols, and finally interactivity and visualization. Hence, the Home Health Care Scheduling and Routing Problem (HHCSRP) was approached from a mathematical optimization perspective. The main objectives are to minimize the total costs associated with travel time and/or distance between locations and the total costs associated with caregiver overtime to improve patient satisfaction by adhering as closely as possible to their time windows, and to maximize workload balance among caregivers by minimizing the working time difference between them.

The use of these methods and technologies contributes to creating more optimized, flexible and intelligent scheduling solutions, as envisioned in the paradigms of OR and AI. Therefore, this work will contribute to institutions better coping with the challenges in decision-making system environments, with regard to the optimization and data analysis requirements of the planning and operational levels. Additionally, this work should contribute to the development of a prototype's conceptual architecture to identify the key elements and issues that must be considered when defining the conditions for proper allocation and balancing scheduling solutions considering the decision maker's preferences. This should serve as a broad guide to help the planner or management choose the best approach, either to acquire an optimal solution or a quick and smart one that considers unforeseen events as they happen.

The following assumptions are considered in the definition of the hypotheses and research questions to be addressed in this thesis and are based on the elements outlined in the previous section as well as the literature reviewed.

- **Optimization methods:** exact techniques, (meta-)heuristics approaches, multi-objective optimization or other optimization strategies may lead to a more efficient allocation of resources, improved patient outcomes, and reduced costs in HHC settings. For example, these methods can help in scheduling home visits for healthcare professionals, routing mobile care units to the right locations, and contribute to a better workload-balancing between care workers. Optimized scheduling impacts patients, caregivers and scheduling coordinators and plays a major role in satisfaction for both the patient and provider. Overall, the use of optimization methods can help to streamline processes, enhance patient care, and ultimately lead to a more sustainable and effective healthcare system.

- **Multi-agent Systems:** scheduling solutions, for example, require modularity, flexibility and adaptability features to deal with the complexity inherent in dynamic and open environments with heterogeneous, distributed, and autonomous components. MAS is an appropriate approach for designing and developing intelligent distributed systems that must exhibit these features. The agent-based approach defines methods for creating interactive, autonomous parts that may perform various functions and have interfaces to work with other parts (physical or micro-services). Although interaction protocols can be used to share information and dynamically adapt the system, their behaviors are driven by events, giving them the autonomy to choose actions.

- **Data digitalization:** the idea is to digitalize the operational management of the service and generate a capability to monitor HHC visits. The goal is to transform data into information and information into knowledge. This work aimed to computerize the route definition process, which involved the creation of two interfaces (web and mobile) to allow the user to change the problem data (e.g., number, locations, and patient characteristics) and to monitor the routes obtained by optimization. The accuracy of model parameters (distances, travel times and treatments) could be improved through collaboration with Google micro-services and real-time data. In addition, the interfaces include interoperability, centrality in the decision-maker and ease of use, which are determining factors for the healthcare system to function without entropy.

This thesis seeks to address the following hypothesis based on the main assumption:

> Optimization algorithms combined with the MAS approach can provide a modular and flexible architecture to design and develop distributed and collaborative scheduling and routing applications, endowed with a database and dashboard for monitoring modules, that can be deployed throughout cloud or mobile apps to address the different objectives of the HHC planning and management.

In this sense, this thesis proposes a smart architecture, comprising a set of differentiated data processing and modules that can be combined, in a flexible way, to serve as an engine for a digital platform that meets the different data requirements, restrictions, and assumptions of operational planning in HHC, as well as the related computational resources and constraints of the tools that can be deployed alongside web and/or mobile applications.

The following research questions are specified to confirm the hypotheses and fulfill the goals of this work:

RQ-1: How to improve decision-making support with faster and more dynamic solutions in HHC scheduling systems, while maintaining an optimized performance?

Scheduling is a crucial but highly complicated process in any industry or service. There are a large number of varied factors that have to be taken into consideration when creating a schedule, and then there are unexpected disruptions that require timely reaction (combinatorial aspect and its dynamic nature). Doing it manually is time-consuming and too inefficient. So, numerous techniques, the more traditional ones that include optimization methods and mathematical formulations, and more recently AI, are used to address this problem. Traditionally, optimization methods were usually centralized approaches, such as classical optimization methods, namely, heuristics, linear programming, or meta-heuristics. However, despite finding optimal (or near optimal) solutions, they could have high response times (instance-dependent to be solved) and considered the problems static and deterministic. In contrast, AI through MAS offers an alternative way to design and control systems, different from the conventional approaches due to intelligent control, autonomy and reactive response, rapidly changing variables needing to be weighed and their inherent capabilities to adapt to emergency situations or disruptions. However, using MAS, in turn, may not complement and/or guarantee to find optimized ("optimal") solutions or operational effectiveness provided by algorithms. Thus, when vital decisions of the scheduling process are bolstered by different planning organizations, dynamic and optimized solutions can be obtained through a modular architecture that allows the cooperation and collaboration of the best of both worlds (optimization and MAS). This modular architecture is an attempt to obtain optimal and innovative solutions, ensuring dynamic responsiveness, timeliness, efficiency and providing organizations with minimal external intervention in planning and routing processes. Additionally, the infrastructure will require interaction mechanisms to share information and perform tasks in a decentralized manner, mitigating the complexities and lack of visibility that planners and programmers constantly face. Furthermore, it should offer interoperability between the components, and enable the system to regulate by simple rules and interactions in an environment without a central authority to address various targets and create reliable scheduling solutions.

RQ-2: What are the main design aspects and criteria that should be considered to support user decision-making regarding deployment, computational time and quality of solutions?

In addition to having an approach to design and develop clever modules endowed with optimization, smart decisions, and/or data analysis capabilities, it is necessary to determine what components should be implemented and where to deploy them, according to the requirements and constraints of the application scenario. For example, with respect to MAS, it will be necessary to investigate the effects of several design factors, such as the number of agents, decision time and message size, on communication-related performance measures used in a system based on bidding or negotiation processes. These performance measures are based on the number of completed processes per unit of time and the time required to complete each process of the system. On the other hand, performing centralized scheduling in terms of computational measures in optimization methods, such as the number of iterations and evaluations and, for example, time requirements, will be important in terms of the decision. Taking these measures into account, it is possible to quantify the degree of benefits and quality of the scheduling solution. This can be achieved by a conceptual outline that should consider the evaluation of several aspects, maintenance costs, concerns, and criteria to identify and design data analysis capabilities, with respect to the key aspects of the application scenario. This should provide some guidelines to help planners and managers to determine the most suitable planning or routing solutions to implement a given task within the scheduling service at HHC. Furthermore, after the application of the developed digital platform in a real-world context, feedback on usability, user experience and user interaction should be collected to identify critical decisions in the system, eliminate conflicts, and generate positive externalities and knowledge for future tasks.

Many planning issues are arising when it comes to planning for public and private HHC providers, but one significant issue is addressed in this thesis: supporting the home care providers by proposing solutions for the operational planning that must be done on a regular basis. This thesis focuses on the routing and scheduling tasks In order to do this, static and dynamic multi-day setting will be specified, incorporating relevant working criteria into the routing and scheduling of care providers and considering unexpected events that may occur in a real environment. In addition, it will be important to solve combined routing and scheduling challenges for instances of real-world problems and evaluate the influence of the solutions of the different approaches. The management of results and manipulation of data is expected to be carried out through a user interface that allows the management of problem data as well as the visualization and monitoring of routes and planning. associated with patients in geographically dispersed locations, matching the required needs to health professionals skills (qualifications and assignment), available resources and priorities or constraints inherent to time windows, periodicities, working regulations (e.g., labor law regulations and work contracts), among others. For this, static and dynamic multi-day setting will be specified, incorporating relevant working criteria into the routing and scheduling of care providers and considering unexpected events that may occur in a real environment. In addition, it will be important to solve combined routing and scheduling challenges for real-world problem instances and evaluate the influence of the solutions from different approaches. It is expected that the management of results and manipulation of data will be carried out through a user interface that allows the management of problem data as well as the visualization and monitoring of routes and planning.

1.3 Scientific Research Methodology

In this project, the traditional design science research approach, depicted in Figure 2, was carried out using the iterative procedure suggested by Peffers et al. [160]. This technique takes into account a nominal process sequence with six steps to create and evaluate artifacts and find a solution to a problem. An artifact is a material or artificial entity created to solve a problem in a specific context. Examples include constructs, models, methods, instantiations and processes [160]. For instance, as stated in Section 1.2, the goal of this research is to create a conceptual infrastructure that offers swarm strategies to support the decision-making of distributed and optimized scheduling solutions that will be deployed on collaborative platforms (web/mobile app), in order to create more adaptable, intelligent, and flexible planning solutions in HHC. In light of the data assumptions, requirements, and/or restrictions of the management and operational level, it will be feasible to contribute to the challenges in dynamic environments.

As previously explained and shown in Figure 2, this methodology is iterative, meaning that the researcher can assess the results at any stage and decide whether it is essential to go back and make changes to the solution artifacts from a previous stage [160]. Based on this, the final solution can be achieved gradually.

The steps outlined in this technique are briefly detailed in the following sections, demonstrating how they are used in this research (Figure 2 - for details, see [160]).

1. Identify Problem & Motivate – includes a review of the literature where, in addition to contextualizing the field, it is necessary to identify a specific research question and explain why finding a solution is challenging. These topics are covered in Sections 1.1 and 1.2 of this study, and they are supported by the literature review conducted and covered in Chapter 2. In conclusion, the research problem focuses on the challenges of effectively distributing and balancing scheduling solutions from different sources or approaches throughout

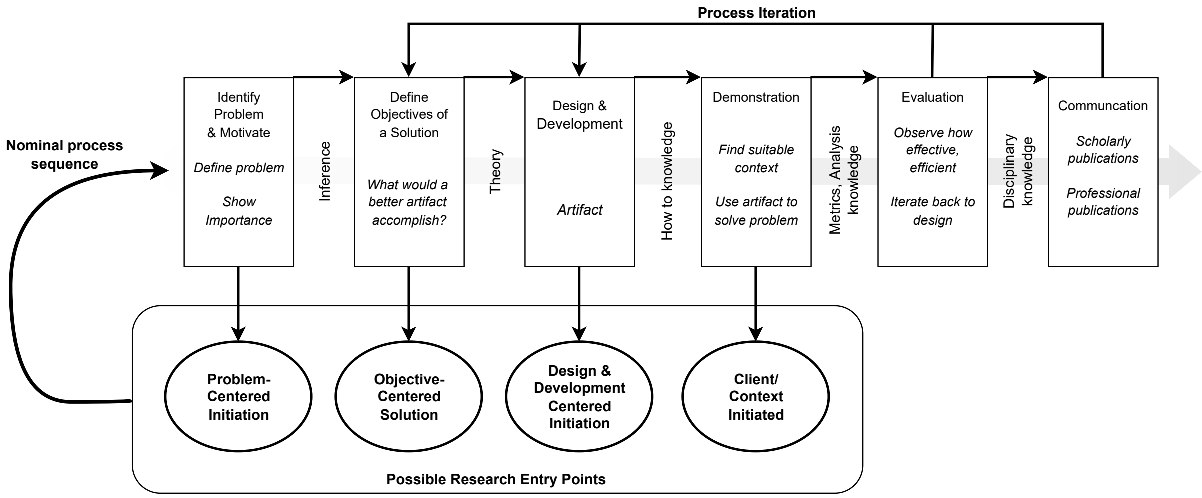

Figure 2: Iterative design science research approach. Source: adapted from Peffers et al. [160].

digital apps, which is vital to generate more intelligent and effective applications in the context of HHC services.

2. Define Objectives of a Solution - based on the main research problem, deduce the goals and specifications while taking into account what is practical and feasible to produce an artifact that can solve the specified issue. As in the previous step, these features are covered in Sections 1.2 of this work, where two research questions are established to guide the creation of this artifact. The first paragraph of this section summarizes the objectives of this work, that aim to produce as an artifact a digitalized process of the HHC scheduling and routing process, which would involve the creation of an application that comprises a set of integrated modules (optimization, database, agent-based system and a dashboard module) in a flexible and collaborative architecture to serve as a general guideline to support optimized and distributed solutions for the management of operational, strategic and tactical HHC services. Furthermore, the user will be able to change the problem data (e.g., number and characteristics of patients), as well as the visualization of the schedule, resources allocation and routes solutions.

3. Design & Development – includes defining the organizational and functional features of the artifact, as well as conceptualizing the solution as something physical or intellectual or transforming the ideas into something usable (conceptual solutions framework). In this work, this is done in Chapter 3 with the presentation of models and design methods for mock-up of the suggested architecture and its more theoretical core principles. In Chapter 4, the description of the use and resources of various modules is introduced as approaches/strategies (implementations and experimental validations) to support the choice of the most appropriate functionalities to deploy and help healthcare/social care providers manage their operations better. In addition, the general guidelines and definition of the designed architecture and their application for outcomes are covered in Chapter 5.

4. Demonstration – includes using the artifact in one or more case studies or real scenarios in the health institution, to show how it can be used to solve the research challenge. The object in this work consists of

a prototype that groups together several of the smart scheduling and optimization mechanisms reported in previous chapters and that is demonstrated in a real-world case study, both of which are covered in Chapter 6.

5. Evaluation - includes the use of quantitative or qualitative indicators to evaluate how the artifact performed when applied and how well it achieved the desired effects. In this study, evaluation is carried out concurrently with the analysis and demonstration of some indicators, which are covered in Chapter 6 and Chapter 7.

6. Communication - includes the communication of the problem, the artifact, and the results obtained with the goal of transferring knowledge to researchers, engineers or other appropriate audiences. This is accomplished in this work through both this report (thesis) and some scientific articles that present relevant aspects of the work described in this document and have been published in conferences and journals.

1.4 Document Organization

This thesis comprises seven chapters and three appendices. After this introductory chapter, which addresses the motivation and purpose of the work, as well as the hypotheses and related research questions, Chapter 2 contextualizes the development of routing and scheduling solutions and conducts a literature review on its methods, technologies, approaches and challenges. Bibliometric analysis is also applied in related studies that propose healthcare planning methodologies and architectures to discuss the state of the art, with a focus on optimization factors, the use of MAS and IT.

Chapter 3 describes the problem definition in a general way, and considers the different application areas. Taking into account that HHCSRP is often solved and enabled with optimization techniques and MAS, this chapter will present different models and methods that will be considered as core strategies for solving the problem.

The suggested and projected infrastructure is presented in Chapter 4. The chapter discusses the main features of the suggested modules and their internal behavior, as well as the techniques, mechanisms and technologies that can be employed to create them. It also demonstrates how the modules can work together and communicate with one another to assist in the creation of a dashboard (web/mobile app) to control the HHC logistics operational service. Database inputs for optimization methods and agent interaction protocols are also described. These can be used to support cooperation between all entities operating at distinct or equal computational levels, depending on the case.

On the other hand, Chapter 5 is essential to quantitatively and qualitatively classify the different implementations and experimental validations (models and methods presented in Chapter 3) carried out throughout the thesis. In general, the different applications and tests performed on an experimental dataset (Health Unit of Bragança) and their performance measurements in global terms will be discussed.

The proposed prototype for identifying and evaluating the requirements, constraints and challenges that managers and developers should keep in mind when designing and creating healthcare applications are presented in Chapter 6. It also includes the customized decision support system, which takes into account several factors to explore and identify the best solutions when deciding how to use a particular HHC route and schedule scenario. From the perspective of the developed smart web/app, Chapter 6 describes how the suggested architecture was put into practice. It also discusses the findings of the preliminary tests that were conducted to evaluate some aspects of the suggested application. The suggested framework and app to assist system managers in choosing the best options to implement and automated planning with a set of operational tasks inside the IPSS - OSPM is evaluated using a real case study.

The main conclusions of this work are presented in Chapter 7, along with a discussion of how the suggested strategy and research questions were addressed as well as the analysis of the main contributions achieved. Additionally, some elements are discussed that could help the current effort to develop in the future.

Finally, Appendix A details the dissemination of results and the awards received.Some of the literature review based on bibliometric analysis that was performed to get a broad perspective on the research carried out in areas related to this work, such as HHC, optimization and scheduling, is detailed in Appendix B. Finally, technical information regarding the developed smart web/app and related general database is also provided in Appendix C. In an effort to help understand how it operates and to facilitate its improvement or replication, they cover the crucial components that were employed to build the computational setup.

1.5 Dissemination Results and Awards

This section presents the dissemination carried out (communications and published papers) as well as some awards achieved during the thesis work. The dissemination of research findings is an important part of the research process, passing the benefits on to other researchers, professional practitioners and the wider community. Research activities supported by public funding are rarely considered complete until results are widely available.

Regarding the papers developed, all the data (theoretical or practical) and experimental results that have been gradually collected were summarized and the relevant results were disseminated through publications in the most prestigious national and international conferences and scientific journals to validate this work during the doctoral period. From the beginning of the doctoral program until the thesis writing, a total of 20 papers were published, 18 of them directly related to the thesis work and 2 works centered on other activities (all of them indexed). It is important to highlight the scientific production of 3 journal articles and 13 book chapters.

The thesis research work generated special recognition, mainly in terms of awards won. Taking into account much of the academic work, whether with more theoretical (conceptual) or empirical (application) methods, they proved to be worthy of some awards given their relevance in the fields of study and the recognition gained by the community. In addition, the work at a technical level allowed to receive four prestigious assessments that deserve due recognition. In Appendix A, this section will be discussed in further detail.

2

Literature Review

> *"Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning." - Albert Einstein.*

Logistics has been defined as organizing and managing the flow of materials, components, supplies, and other resources from suppliers, through the organization's process, to customers [89, 192]. In particular, health logistics, over the years, has led to several strategic, tactical and operational problems, such as scheduling and routing, often varying in terms of the distribution policy involved [75].

To operate efficiently, organizations need the best compromise in solving routing and scheduling problems, in order to optimize solutions, balance the capital, and also generate savings, due to the huge increase in fuel costs, maintenance costs, increasing salaries, customer satisfaction, among others, which generate the largest percentage of an organization's operating costs.

Generally, the distribution of goods, services, or products is the determination of the most effective and efficient way to generate transport (how, when and by whom) from the depot to the customers. The logistics associated with these problems occur in the public - school buses and drivers for mass transit systems - and private sectors - tractor-trailers, airplane and aircrew routing and scheduling services.

The output of routing and scheduling problems consists of a set of entities to be serviced in a specific order and the time of day to service these entities. In strategic terms, routing and scheduling problems have issues, as they generally consider time horizons, greater uncertainty, and require higher capital resources than tactical issues (updates or alterations). Normally, issues about depot and facility locations are more strategic, while vehicle scheduling and composition problems are tactical. When coupled with an effective management information system, routing and scheduling methodology plays a critical role in operational planning [39]. Generally speaking, cost minimization is the main objective of most routing and scheduling problems.

Based on that, this chapter presents the literature review carried out to answer the research questions of this thesis, defined in Section 1.2. In particular, it discusses the main strategies, aspects, technologies and approaches involved in designing and developing scheduling and routing solutions, especially considering data analysis in HHC problems.

The remainder of this chapter is structured as follows:

- Section 2.1 - presents an overview of the main aspects of scheduling and routing, contextualizing their problems and solutions that have been considered in many paradigms for the development of new strategies in the logistics systems of organizations.

- Section 2.2 - presents the paradigms of problem(s) considered in real-world health systems, providing various complementary features and technologies/approaches to support the development of solutions.
- Section 2.3 - addresses the main aspects of proposed approaches to design and develop scheduling and routing solutions for HHC. Furthermore, discusses the main benefits found, drawbacks, associated trade-offs and related challenges, including a bibliometric analysis.

2.1 Scheduling and Routing – State-of-the-Art

The classification of the basic output of all routing systems and scheduling problems is almost always the same: for each vehicle or driver, a route and a schedule are provided [40]. Generally, a route is a sequence of locations that must be visited, and the schedule identifies the job or activity of planning the times in which the particular task will be carried out [169, 164]. Thus, for example, from a certain location (depot x) it is possible to carry out a certain activity (e.g., pickup or delivery) to the customer number y. The start of this route and schedule can take place at time 10 am and is in charge of a specific vehicle (e.g., vehicle 1). This simple example can be replicated for more depots, activities, customer numbers, times and vehicles.

Nowadays, there are some characteristics where routing and scheduling problems can differ:

- size of vehicle fleet (one or more);
- type of fleet (homogeneous or not);
- nature of demands (deterministic or stochastic);
- location of demands (at nodes, on arcs);
- underlying network (undirected, directed, and mixed);
- vehicle capacity;
- maximum vehicle route-times;
- costs (e.g., fuel);
- operations (pickups, drop-offs, mixed);
- objective (minimize costs, number of vehicles, etc.);
- among others.

Most scheduling and routing situations or problems will affect other parts of the organization. In other words, changing routes and schedules forces the institution to make adjustments in its other operations, such as customer lists, database, maintenance, emergency services, etc.

The term “scheduling and routing challenge” refers to situations in which workers are mobilized to perform work-related tasks in several places. In these situations, employees travel by a variety of modes, including walking, driving, public transportation, and biking, among others, traveling between the visit locations to accomplish the task. This creates problems with both vehicle routing and employee scheduling. Although the number of activities varies depending on the length of the work shift, a routing issue also develops if it is assumed that each activity must be carried out at a different location. And for that, routing and scheduling are necessary for work activities that must be completed in a certain amount of time [52]. Most scheduling and routing problems consider the node where the demand for service occurs at specific location or the edge of the connections among the locations and still examine constraints on service, such as time windows, dependencies, and periodicity, among others. For these reasons, there are a large number of works in the literature on vehicle routing and scheduling problems [39, 40].

Some scenarios that combine these properties are health professionals (or caregivers) visiting patients at their homes to provide some type of care/treatment [53], care workers helping members of the community to perform difficult tasks [77], and security guards performing night rounds on several premises [148], among others.

The basic routing problem is easy to state. Considering a set of given nodes and/or edges that need to be served by a fleet of vehicles, and assuming that there are no constraints, we have to guarantee the visit of all nodes and identify the order or sequence of visits. The problem is to construct a feasible and low-cost set of routes for each vehicle.

First named and documented in the late 1950s, Vehicle Routing Problem (VRP) explores the logistics of routing efficiency. This problem deals with a range of variables including vehicles, drivers, depots, roads, and customers, and can accomplish any number of goals, such as accommodating a change in the fleet, such as an unexpected breakdown; minimizing the number of delayed orders when a sudden spike in demand arises; or, commonly found, ensuring that the fleet is operating as efficiently as possible to minimize the transportation costs [194].

On the other hand, scheduling is a crucial but highly complicated process in any industry. There is a huge number of factors that have to be taken into consideration when creating a schedule and then there are unexpected disruptions that require a timely reaction. Doing this manually is time-consuming and and very inefficient.

Schedule optimization is about constructing a schedule that will be as efficient as possible by allocating the right number of resources to the right places at the right times. It is also referred to as dynamic (or distributed) scheduling since the schedule often has to be dynamically adjusted in reaction to changes or disruptions (such as workers calling in sick, equipment failure, traffic conditions, among others) [164].

Depending on the industry and management domain, scheduling may refer to:

- production planning;
- workforce planning (rostering and distributing staff);
- transportation planning and routing;
- project workflow planning, etc.

Before explaining how to optimize the scheduling process, the problem in general should be described. In this way, there are several main factors that must be considered, namely, hard and soft constraints, Key Performance Indicator (KPI), the objectives, amount of work, available resources and the expenses involved.

Available resources might include staff, equipment, vehicles, raw materials, assembly lines, and so on. The amount of work to be done can relate to the expected level of demand to be fulfilled, number of goods manufactured, number of services provided, etc. Monetary expenses are any operating or capital expenditures that impact the financial result, such as payroll, overtime compensation, mileage costs, shrinkage, depreciation, storage costs, etc. Hard operating constraints are limitations that cannot be changed and must be considered. They include government and union labor regulations (like the number of working and overtime hours per week), physical constraints (like the distance between stops or assembly lines), the exact number of raw materials for the production of items, number of certified workers per shift/activity, etc. The capacity and throughput limitations can also be included into this category, such as the number of items a warehouse can hold, number of patients that one health professional can serve, amount of time required to travel between appointments, and so on. Soft constraints are those that are desirable, but not mandatory, such as individual employee preferences (worker A wants to work with worker B, health professional X does not want to work the night shift, technician Z wants a vacation in July, etc.), order or customer prioritization, etc. Business and/or service objectives are the goals to be achieved, such as maximizing profit or the number of items produced or minimizing costs, risks, idle time, empty mileage, etc. Metrics or KPIs are measurements that show the effectiveness of the schedule and can be compared to support decision-making.

In this regard, many scheduling and routing problems have been tackled in the literature, such as a variety of applications in the industrial and service sectors (e.g., HHC), from logistics and transportation systems to material handling systems in manufacturing [52, 69].

In turn, this thesis seeks to deal with scheduling and routing problems in real contexts, giving special focus to the HHC services problem, which will be presented and detailed in the next section.

2.2 Home Health Care Problem

HHC institutions aim to provide care and/or services to patients, at their homes, ensuring the quality of service, while controlling costs and improving working and living conditions. In general, the HHC intends to provide patients with medical or paramedical services in the comfort of their own homes, promoting family stability and well-being. In addition, these services allow for reducing the number of occupied beds in conventional hospitals.

Thus, HHC has seen significant growth in recent years, which is partly due to the aging population. Taking Portugal as an example, the National Health Service, created in 1979, is the basis of the Portuguese healthcare system [156]. The provision of long-term care services has traditionally been the responsibility of families and social solidarity institutions in Portugal, while public provision played a minor role. This changed when LTCNN started in 2007. The LTCNN is decentralized and supported by three levels of coordination: local (local coordination teams closely allied with primary care); regional (five regional coordination teams focused on identifying regional needs and implementing regional activities); and national (implementation, management and monitoring).

The Portuguese population is expected to age significantly by 2050, when 32% of the population will be aged 65 and over and around 11% will be aged 80 or over, compared to an Organization for Economic Cooperation and Development (OECD) average of 25.7% and 10%, respectively. Quality assurance of long-term care services has been a policy priority since the introduction of LTCNN. This is an outstanding example of an integrated approach involving health and social service agents. The good features of the LTCNN system are:

- an information systems integration strategythrough information portability;
- the use of integrated evaluation tools and multidisciplinary care assessment for patients requiring long-term and post-acute care;

- the ongoing process of needs assessment, ongoing monitoring of care recipients' conditions and benchmarking of results at the national, regional, local, and unit levels are all made possible by the usage of an online web-based system;

- the use of local coordination teams that establish standards mainly in infrastructure and personnel.

However, despite the difficulties, Portugal has some qualified care workers but few people receive care services. In 2011, there were 4 long-term care workers in institutions for every 1000 people aged 65 and over, compared to an OECD average of 3.2 [155].

As shown in Figure 3, HHC creates many more organizational challenges than a traditional hospital service, even though this may result in potential hospitalization cost reductions. Patients receive care at home and can be spread over a large area, therefore the HHC agency must manage several mobile internal resources (mainly human resources with specialized skills and limitations, but also physical resources such as vehicles) as well as some external resources (pharmacies, laboratories, etc.).

Figure 3: HHC Organizational challenges.

The development of HHC solutions, even in terms of routing and scheduling, has been the scope of many disciplinary fields. This expanding sector has opened up many research avenues of industrial engineering and optimization, as shown in Figure 3.

Over the years, there have been studies that have already analyzed uncertainty factors and stochastic events associated with HHC services, namely, dynamic travel time, care length, change in patient needs, etc.). In addition, some works consider the wide range of care workers with different skills and limitations (nurse, auxiliary nurse, physiotherapist, etc.); the significant importance of the human element, which directly affects admission (family preference); assignment of the care workers (limitation, human compatibility), routes (human limitations on schedules); the significance of quality of service, which is the main objective in this industry, even though costs are obviously very important. It is possible point to some works, in particular: the division of the territory and the proper distribution of resources to each district according to different criteria [34]; optimization of the admission process for new patients coming from hospitals to home health care [117], among other optimization studies.

For this work, a literature review focus on HHCSRP, more related with operational aspects. When dealing with such issues, it is necessary to allocate responsibilities to HHC agency employees, schedule visiting times for a group of patients, and plan the routes of the care providers while taking into account operational and legal restrictions.

Some reviews and studies of the existing literature, such as Gutiérrez & Vidal [106] give a general overview of logistic problems in the HHC field. Various OR applications are also detailed Sahin and Matta [177]. On the other hand, Becker, Lorig, and Timm [30], give an overview of approaches using MAS in order to support planning and scheduling in HHC. More recently, Grieco, Utley, and Crowe [102] evaluated the strategies and problem-solving techniques used OR to solve the various choice difficulties in HHC.

Other reviews focus more on the HHCSRP, as is the case with the work of Fikar and Hirsch [86] that provided a comprehensive survey of the HHC literature while focusing on the most typical factors in routing and scheduling issues. Later, Cissé et al., [54] conducted a literature review of OR models used with the HHCSRP.

The main goal of this section is to determine the main restrictions, constraints, and objectives in particular for routing and scheduling issues in the HHC setting.

2.2.1 Routing and Scheduling problem in HHC

HHC problem can be defined as a set of human and material resources used to provide the required services to patients at their homes. The HHCSRP is a known combinatorial problem that has been studied for many years. According to Cissé et al. [54]: *"The home health care routing and scheduling problem consist of designing a set of routes used by care workers to provide care to patients who live in the same geographic area and who must be treated at home."*

In HHCSRP, a group of patients spread across a certain territory who require care at their homes for different periods of time and with specific qualifications is considered. Care workers with various skills and availability under the management of an organization HHC provide this type of care. The left part of Figure 4 shows an illustration of such an issue, with one HHC unit caring for 10 patients. Each patient is given a time window, preferences, or visit periodicity that reflects their availability as well as a treatment that represents the duration of their visit. To each arc connecting two patients, weights can be applied. These weights typically reflect the cost of travel or the distance between two patients.

Typically, care workers leave the HHC unit (depot) and return there at the end of their shift using a variety of modes of transportation (most commonly a vehicle, although they can also take public transportation, cycle, or walk). The HHCSRP involves selecting which care worker visits which patient and when, while following a variety of constraints and minimizing or maximizing certain parameters (such as cost or service quality), over a predetermined period of time. In the case of three care workers visiting 10 patients, the results are a set of routes that indicate the scheduled visits, as seen in the right part of Figure 4.

Thus, the well-known and extensively researched VRP and HHCSRP are related [57]. This challenge aims to identify a set of routes that minimize the overall distance or time traveled by a set of vehicles while visiting a set of clients (in order to satisfy the requirements of each client) dispersed across different locations. Each customer must be visited by only one of the vehicles, and all routes start and stop at the same depot (the HHC institution). For example, HHC scheduling means that patients and their families know what to expect from their care program

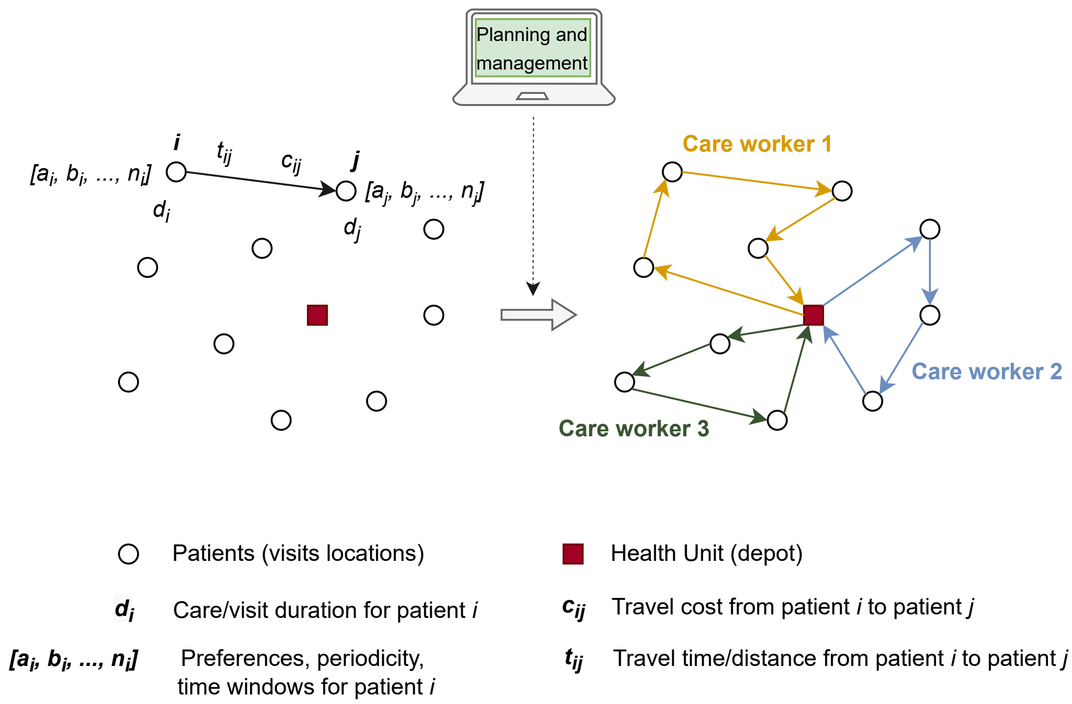

Figure 4: Example of an HHCSRP problem/solution with three care workers and 10 patients.

and can plan accordingly, assigning health care professionals (e.g. nurses or care workers) to a detailed route and schedule.

Many of the problems in the literature consider variants of VRP, such as VRP with time windows, pickup and delivery, periodic, multiple depots, with heterogeneous vehicles, among others [72].

Traditionally, the main objective of HHCSRP is to minimize the standard costs associated with routes (such as travel costs – time or distance) and personnel (such as overtime costs) [86]. Preferences, visiting hours, and/or periodicity of staff and patients are usually the second type of objective function criteria. For that reason, the HHCSRP can be described as a combination of the VRP variations mentioned in the previous paragraphs [86]. Patients have a time window during which they must receive health or social care. Rather than departing from a central depot, the care workers begin and end their routes at the health institution and the visits are site-specific (not all care workers can help all patients).

The models and formulations are customized to suit the specific environment for which they were developed. In fact, there are differences between various nations, regions, and institutions in the types of infrastructure, available physical resources, patients and health professionals or caregivers.

2.2.2 Main Features found in HHCSRP

One of the main features is the visits to the patients themselves and their inherent characteristics. Health professionals are required to make a certain number of home visits to patients. A visit is the act of providing care to a specific patient by exactly one care worker who provides the care the patient needs. Although a care period is often fixed, in some circumstances it may be based on the skill of the care provider, the daily need, or some unexpected event. A patient may require one, or more visits, during the time considered. When a patient requires several visits, certain time dependencies between the care visits may be more complicated than the traditional precedence restrictions.

An example of this situation is the periodic characteristics of visits, which consider a certain frequency of visits (for example, visiting that particular patient every Wednesday morning and Friday afternoon). Furthermore, precedence restrictions must always be considered, which determines that the next patient is visited when the previous one is finished and so on, always taking into account the sequence of planning already obtained or to be proposed.

Another important feature of the HHCSRP problem is the care workers. Different care providers with different skills are typically considered nurses, auxiliary nurses, or care technicians. They are typically represented by various skill levels, and occasionally a care provider may only perform tasks that exactly match that skill level or a lower one. All care providers typically start and finish their shift at the home health care agency (depot). They have a wide range of modes of transportation, including their own vehicles, buses, motorcycles, and foot. In addition to the traditional time windows limitations representing caregivers availability, one might also need to adhere to a set of legal regulations (such as a lunch break or maximum working time) to seek an improvement in workload balance. Finally, there may occasionally be incompatibilities between certain healthcare professionals and certain patients (gender, language, allergy, among others).

However, the central element of the problem is undoubtedly the patients. For this, it is also necessary to take into account that the travel time between patients and between patients and the HHC agency is known, although occasionally with uncertainty, just as in traditional VRP. In addition, patients can express their preferences for visits, such as gender of the care worker and/or incompatibilities, desired availability time window, periodic visits, etc.

The majority of HHCSRP literature focuses on assigning a care worker (with an associated vehicle) to a patient and on figuring out the care workers optimal routes with respect to the patient's appointments or demands (should be fulfilled within the available time). In addition to these 3 main features, there are other optimization criteria that can and should be considered:

- Time (e.g., travel, waiting, uptime, overtime);
- Costs (e.g. travel, waiting, assignment, resources);
- Traveled distances (e.g., costs, CO2 emissions);
- Workload balance (e.g., number of patients, time duration);
- Patient preference (e.g., care worker assignment for continuity of care, unavailability);
- Caregiver preference (e.g. lunch break, unavailability)
- Unsatisfied services (e.g. dissatisfaction rate);
- Number of used caregivers (e.g. use rate).

However, there may still be specific features that relate to the common constraints to which the problem is subject, which are as follows:

- Time windows - in terms of availability and unavailability (from patients to healthcare professionals);
- Qualification - skills to perform the care and treatments;
- Synchronization - precedence synchronization in terms of service activities that should be well organized;

- Working Regulations - hours, break times, overtime, among others;
- Periodicity - how many times some activities are repeated (e.g. visits);
- Planning Horizon - single-period or multi-period planning.

Thus, all these features will lead to models with new and more complex objectives or constraints compared to the classic VRP.

Note that, not only home health problems are considered, but also problems with home care or home services, which include non-medical services aimed at assisting elderly and, more generally, vulnerable people in daily activities, such as housekeeping, meal preparation, bathing, etc. The reason for this is that HHC institutions face similar routing and scheduling issues as Home Care and Home Service agencies, with the key difference being data. As a result, it is important to refer that "staff members" rather than "care or nurse workers" and "visits" rather than "care" or "services", but we will still refer to "patients" throughout even for "beneficiaries" of home services.

2.3 Related Work and Bibliometric Analysis

This section aims to highlight the existing and related work in the area of HHC settings, procedures, and operational management, essentially in the domains of OR and AI, and problems in the context of scheduling and routing. A bibliometric analysis is a study that aims to uncover the fundamental structure of a research area. It analyzes research trends in depth, evaluates science as a product knowledge system, and is trustworthy and objective.

Thus, the main goal is to conduct a literature survey and a bibliometric analysis, considering a numerical analysis of the related work that is currently available, taking into account keywords (or combinations) used in journals, conferences, countries Additionally, detailed tables are provided that group articles according to certain characteristics, especially taking into account factors of real-life problems and/or applications, especially in the context of HHCSRP.

2.3.1 Methodology and Procedures

The collecting and selecting process of the analyzed papers carried out to define the discussion this thesis is described below. Initially, a methodology was defined that aims to refer to the highest level of the general development of the scientific field achieved at a particular time (between the years 2010 and 2022), related to the areas of the thesis. The general procedures can be seen in Figure 5, which explains the strategy from the definition of keywords and generation of the search query to the graphic visualization of the data collected, pre-processed and analyzed.

Recalling again the research questions RQ-1: and RQ-2: defined in Chapter 1, a list of relevant keywords was considered and defined to answer the research in terms of the areas under study, and later serve as input for the database search. Different possibilities of "Keywords Combinations" were tested in the two databases classically used in OR, namely Scopus and Web Of Science (WoS), and with some resourse to Google Scholar (but without the priority of the first two databases). The selected keywords were relatively generic to avoid missing any relevant papers. In terms of keyword combinations, the following was considered:

1. ("home health care" OR "home care" OR "home service" OR "health care" OR healthcare OR "home healthcare" OR "home health nursing" OR "long term care");

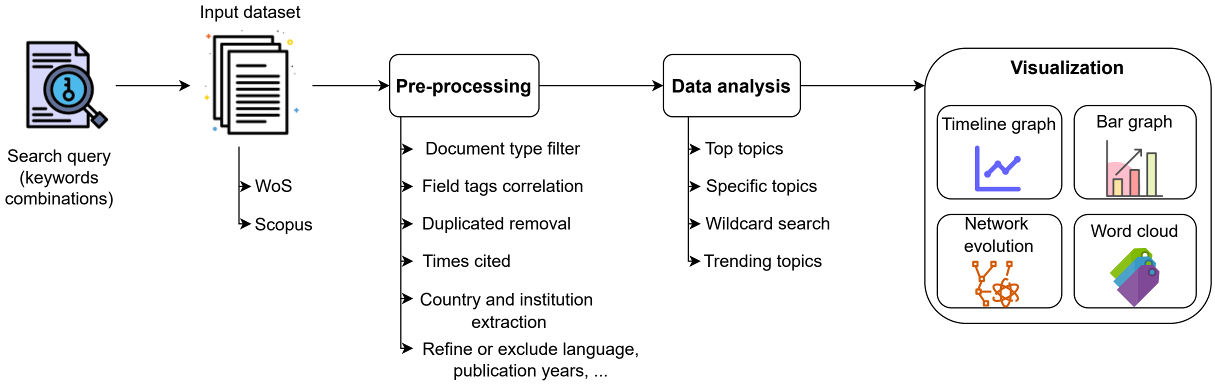

Figure 5: Main features for collecting and analyzing the state-of-the-art and performing a bibliometric analysis.

2. (scheduling OR routing OR planning);
3. (Optimization OR Optimisation OR "multi-agent system" OR "multiagent system" OR "agent-based system" OR multi-agent OR "multi-agent");

These keywords were chosen because they identify the main concepts of the research topic and describe the topic of study (item 1), the problems involved (item 2) and the possible solution strategies (item 3). In addition, keyword selection is a multi-step process involving identifying topics, brainstorming synonyms and antonyms that could also describe the topic and spell out abbreviations.

The methodology involves generating links between the keywords defined in 1, 2 and 3, both in terms of title, abstract and keywords or topics, and betting on the general combination of each item (combine queries 1 *AND* 2 *AND* 3).

The initial search did not use any limitations and resulted in a large number of articles, preferably in English, for each database. For that reason, it was necessary to carry out a pre-processing to limit the collection of articles, which in the first phase was limited by context (engineering, computer science, operations research management, mathematics, business, management and decision science), that is, dominant areas of the research work spectrum. The articles were chosen after careful consideration of the title, keywords, and abstract. This allowed for the differentiation of some of the papers' categories (document type filter), such as whether they were published as journal papers, conference papers, book chapters, or technical reports. It was decided to keep only journal and conference papers for this work, focusing on the end tag for the publication stage. It is also important to mention that some documents with keywords outside the operational context of HHC were excluded, namely keywords that referred to "Wireless Sensor Network(s)", "Energy efficiency", "Sensor nodes", "Power management (telecommunication)", among other complementary ones.

Thus, after applying some pre-processing (document type, tags, times cited, refining search only for English language and years restriction), a total of 1763 papers were obtained, belonging to the vast majority of the Scopus and WoS database. After a brief analysis, it was possible to verify that some papers were omitted; in others, it was possible to remove duplicate papers (359 papers) that would have been replicated. Therefore, 1404 papers were pre-processed for further bibliometric analysis.

However, it is almost impossible to guarantee an exhaustive view and analysis of all pre-selected papers, it was defined that the main objective is to highlight documents through some faster filters (data analysis), such as highly cited papers, top subjects, open access, or those documents that are main references and trends for this type of topics. Other criteria must be met, such as the focus on HHC, that is, the purpose and objectives must explicitly address HHC concerns, eliminating redundancy factors. Another criterion is that the articles address planning, routing, and scheduling problems within a HHC context, which has high levels of citations and references, from 2010 to 2022. The development of the scope of this section of work was made possible by studies such as those by Cissé et al. [54] and Di Mascolo et al. [70]. With this strategy, of the 1404 papers, it was possible to define, evaluate and present 39 journal papers and 13 conference papers. The adopted rule regarding the selected journal papers was to present at least one work for each year considered in the analysis, and that it be highly cited and recognized by the scientific community in the previously defined criteria. It should be noted that the oldest works, from 2010 or 2011, are not always the most cited, but were chosen to highlight the research area on an annual basis and over the years, and that from 2010 onwards has been growing exponentially, hence the more recent years have included the selection and analysis of more works. In addition to the aforementioned criteria, the journal could be selected for analysis if it had a percentage above 20 citations (admissible value), with the vast majority greater than 100. As for the strategy for selecting conference papers, the idea was similar, but in turn, due to lower visibility, only one paper was chosen for each of the years considered.

In this sense, a data analysis (information extraction) was carried out based on a reduced selection of papers, taking into account the factors mentioned above. Table 1 presents some quantitative and qualitative outcomes of the selected journal papers reviewed related to HHC routing and scheduling. Some general characteristics, such as the publication journal, the solving procedure, whether it is a case study or more theoretical (review), and what is the objective inherent to the work, namely in the minimization of "more classic" objectives (e.g., time or distance costs) or the possibility of considering other ("more recent") objectives, such as the presence of uncertainties, health professionals or patient preferences, emergencies, time windows, periodic visits, workload-balancing, among others, are presented.

Analyzing the journal papers publication year, the increased number of papers addressing HHC routing and scheduling is significant, especially in recent years. It is possible to verify that the journals with the highest number of publications are in the fields of Operations Research, Manufacturing and Production Research, Computer Science and Mathematics. Some interesting works in the fields of Healthcare Management were also found and selected. Furthermore, some of the most common solving approaches are Mixed Integer Linear Programming (MILP), Constraint satisfaction problem (CSP), Constraint Programming (CP), Column Generation (CG), Branch & Price (BP), MAS, Lagrangian relaxation (LR), epsilon constraint (ϵ-method) and specific metaheuristics, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Tabu Search (TS), among others. The majority of work proposes a linear model and often tests it using linear solvers like CPLEX. However, many works also use metaheuristics (such as evolutionary algorithms, simulated annealing, among others) in combination with data from other types of software (e.g., MatLab). More advanced methods, such as decomposition, multi-objective optimization (MO), or hybrid methods, are increasingly being considered in recent work. In terms of the objective of the work, the works were divided into two categories, namely the standard minimization of specific goals (time, costs or distance) and others (preferences, unexpected events, time windows, frequency, among others). Furthermore, important literature reviews of HHCSRP and its variations have been published by Fikar and Hirsch [86], Cissé et al. [54], Grieco et al. [102], and Di Mascolo et al. [70].

The information present in the publication can, sometimes, be different depending on the type of publication (e.g., conference papers). In this sense, Table 2 describes some documents analyzed from conferences (one for

Table 1: Overview of the general charecteristics of the publications of the analyzed journals papers.

Year	Reference	Publication Journal	Solving Approach	Problem		Objective	
				Case Study	Review	Min travel time/cost/ distance	Others
2010	Wei et al. [103]	IJHG	MO - CSP	X		X	
2011	Trautsamwieser and Hirsch [195]	JAOR	MILP - VNS	X		X	X
2012	Nickel et al. [153]	EJOR	ALNS - CP	X		X	X
2012	Rasmussen et al. [170]	EJOR	MILP – B&P	X		X	X
2013	Allaoua et al. [3]	ENDM	MILP – Matheuristic	X		X	X
2014	Cappanera and Scutellà [45]	Trans. Science	-	X		X	X
2014	Carello and Lanzarone [47]	EJOR	CC	X		X	X
2014	Lanzarone and Matta [120]	ORHC	-	X		X	X
2014	Mankowska et al. [138]	HCMS	AVNS - MILP	X		X	
2015	Fikar and Hirsch [85]	J. Clean. Prod	2 st. Matheuristics	X		X	X
2015	Shakshuki and Reid [178]	Procedia Comput. Sci.	MAS		X	X	X
2015	Hiermann et al. [110]	Central EJOR	2 appr. MILP - CP	X		X	X
2015	Yuan et al. [212]	IJPR	MILP – CG- B-P	X		X	X
2015	Sahin and Matta [177]	IJLRA	-		X		
2016	Braekers et al. [42]	EJOR	MILP – ALNS	X		X	X
2016	Fikar et al. [87]	EJIE	Matheuristic	X			X
2016	Rest and Hirsch [173]	FSM	MILP – TS	X		X	X
2016	Wirnitzer et al. [206]	ORHC	MIP Approach	X		X	X
2016	Yalçindag et al. [211]	C&OR	MILP – 2st. approach	X		X	X
2017	Cappanera et al. [46]	Omega	CC	X		X	X
2017	Cissé et al. [54]	ORHC	-		X		
2017	Fikar and Hirsch [86]	C&OR	-		X		
2017	Liu et al. [134]	IJPR	MILP - B&P	X		X	
2017	Marcon et al. [139]	SMPT	Sim - MAS	X		X	X
2018	Decerle et al. [63]	ORHC	MA	X		X	X
2018	Fathollahi-Fard et al. [82]	JCP	MILP, (Meta-)Heuristics	X		X	
2018	Lin et al. [132]	C&IE	Metaheuristic	X		X	X
2018	Zhan and Wan [213]	C&OR	MIP - heuristic	X		X	X
2019	Decerle et al (a). [62]	SEC	MILP - MA - ACO	X		X	X
2019	Decerle et al (b). [64]	SEC	MILP - trade off analysis	X		X	X
2019	Fathollahi-Fard et al. [81]	NCA	Lagra. relax. - Heuristics	X		X	
2019	Gomes and Ramos [100]	EJOR	MILP	X		X	X
2019	Grenouilleau et al. [101]	EJOR	Heuristic - LNS	X		X	
2019	Liu et al. [133]	C&OR	ANS	X		X	X
2020	Fathollahi-Fard et al. [83]	ASC	MO, Fuzzy, Metaheuristics	X			X
2020	Restrepo et al. [174]	Omega	2-stage stochastic prog.			X	X
2021	Demirbilek et al. [66]	FSMJ	Heurstic appr.	X		X	X
2021	Di Mascolo et al. [70]	C&IE	-		X		
2022	Fathollahi-Fard et al. [80]	Symmetry	MO - LR - ϵ-method	X		X	X

each year of the period covered), which throughout the analysis period were and still are part of the state-of-the-art in HHCSRP. Once again, in recent years, the routing and scheduling problem has received a lot of interest with immense research dissemination at national level and international conferences around the world.

Table 2 shows that, among various publications, most papers are published in fields such as automatic control, operations research, computational science, optimization, management, and in the HHC context. There are also some conference publications that allow attesting to some of the problems in applied case studies, namely, in terms of the national context of the authors (for example, applied case studies in Portugal and Austria). Most published works analyze and solve problems according to case studies provided by instances present in the literature or by random data generation. In turn, some works suggest case studies applied in a real context, as is the case of Portugal and Austria, namely with the collaboration of health entities. Once again, the authors prefer applications directed towards objectives that optimize costs (minimization of times, distances and/or costs), leaving dynamic goals in the background, which include, for example, more dynamic aspects and distributed studies that consider unexpected information and/or emergencies, real-time data or restrictions on assigning preferences and route continuity.

Table 2: Overview of general characteristics of the analyzed conference publications.

Year	Reference	Conference Publication	Solving Approach	Problem		Objective	
				Case Study	Review	Optimize Costs	Dynamic Goals
2010	Misir et al. [147]	CEC	MILP – Heuristics	X		X	
2011	Redjem et al. [171]	IEEE CASE	MILP	X		X	
2012	Rendl et al. [172]	CPAIOR	CP - VND, VNS, EA, SA	X		X	
2013	Mutingi and Mbohwa. [150]	IEEM	-		X		
2014	Yalçındağ et al. [210]	HCSE	Decomposition - Kernel Regression	X		X	
2015	Rest and Hirsch. [65]	IFAC	TS	Austria		X	X
2016	Decerle et al. [65]	IFAC	MIP – Two phase Matheuristic	X		X	
2017	Alves et al. [16]	ICCSA	GA & PSO	Portugal		X	
2018	Alves et al. [19]	PAAMS	MAS - GA	Portugal		X	
2019	Alves et al. [23]	ICORES	Tchebycheff method - GA	Portugal		X	
2020	Bazirha et al. [29]	IEEE GOL	CPLEX - GA	X		X	
2021	Makboul et al. [137]	IFIP AICT	CPLEX - MILP	X		X	X
2022	Alves et al. [13]	SOHOMA	MAS	X		X	X

The results of Tables 1 and 2 show that the vast majority of works used optimization methods and models as a solving approach or study review applied to HHC. In this sense, it is verified that there are few approaches that use MAS (only two journal papers, one of which is a review and two conference papers). This means that there are still few studies and works using MAS and some of the reasons this happens can include technological constraints (feasibility), a less obvious option (less publicity), and resource constraints (less accessibility to programming resources). However, this fact may, on the one hand, sustain that this work is innovative, or on the other hand, it may be difficult to implement.

Since almost all the analyzed papers model the routing and scheduling problem in the HHC context as an extension of VRP, travel criteria are almost always considered. However, most works consider more than one objective (multi-criteria approach), therefore, journal papers are often quite complete.

Due to the importance of primary health and social care for the elderly population, but generally due to the contribution of communication, the routing and scheduling problem in the context HHC has received increasing attention in recent years, and now even more due to the situation of the COVID-19 pandemic. Figure 6 describes some of the main features identified when analyzing the papers. The features marked in bold are the most common ones in terms of representativeness and importance given in the identified works.

Regarding the HHCSRP problem, in addition to covering a wide variety of applications, as a rule, authors use real-life instances to validate their approaches. Output functions (objectives), inputs, constraints (the belt that tightens the HHC system), and the optimization procedures, are numerous. Most of the papers collected and analyzed are extensions of the VRP, considering classic objectives (such as travel costs) or constraints (such as time windows, legislative restrictions, skills, etc.). Research points to new considerations, namely unusual constraints (such as dependency constraints, continuity of care, etc.) or dynamic aspects, and uncertainties as input values, which are very close to real-life cases [102]. The parameters (variables), size of the problem, constraints, and objectives, as well as the speed and quality of the solution found, are the main determinants of any solution approach (final solution).

In summary, the works by Fikar and Hirsch [86] and Cissé et al., [54] bring together much of the previous work regarding global citations, representative of an extensive review of the topic in question. On the other hand, there are many case studies that use real data from health organizations. The development of applications for HHCSRP remains extremely current (COVID-19 pandemic), always looking for better optimization, the best approach with

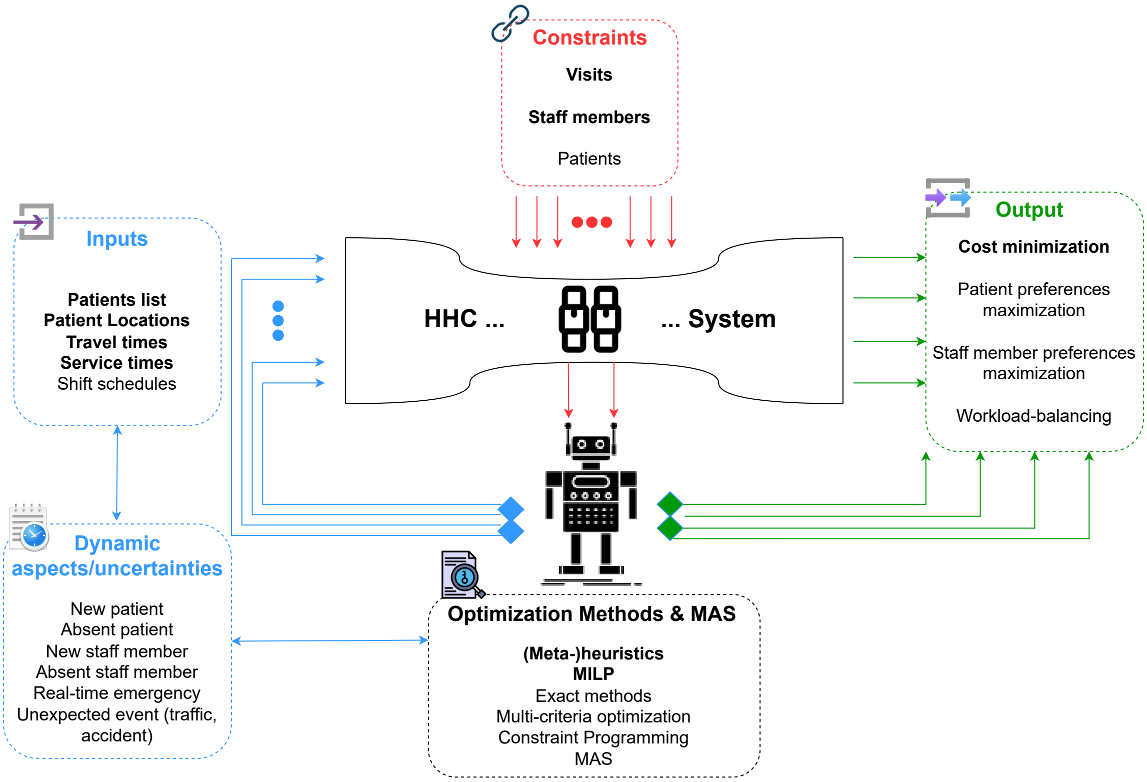

Figure 6: HHC system and main features of the analyzed papers.

robust and fast solutions [80], strengthening the growing need for service and an increasingly common topic in the community. The HHC services find numerous challenges as a result of the unpredictable nature of service delivery in the home health setting.

2.3.2 Bibliometric Analysis

Bibliometric analysis is an indispensable statistical tool for mapping the state-of-the-art in a given area of scientific knowledge and identifying essential information for various purposes, such as prospecting research opportunities and substantiating scientific research. Furthermore, bibliometric analysis is a growing research field supported by different tools. Some of these tools are based on network representation or thematic analysis.

In this work, a new open-source scientometric Python tool called ScientoPy was used [175]. This tool allowed dealing with the difficulties associated with Scopus and WoS sources, namely document filtering, duplicate document removal, h-index extractions and representation for the analysis topic, brief graphical pre-processing, the use of graphical user interface, and offers a set of temporal analysis possibilities for authors, institutions, wildcards, and trending topics using four different visualization options. It enables future bibliometric analysis in different emerging fields [175]. In addition, and in order to complement this section, the Bibliometrix R-package was also used [26]. It is important to remark that nowadays the Bibliometrix is more than just a statistical tool, it includes all the main methods of bibliometric analysis, especially for science mapping and networks, and is not intended to measure science, scientists, or scientific productivity. For this purpose, the interface for Bibliometrix, called Biblioshiny was used. A third tool was also used to analyze and build indicators on the dynamics and evolution of scientific information, which can be seen in the Appendix B, where more details of the bibliometric analysis process can be found.

In this sense, a brief bibliometric analysis was carried out taking into account the 1404 documents initially collected from the databases, between 2010 and 2022. Basically, this analysis consisted of looking for the main reference set on the routing and scheduling problem, which will mostly be problems in HHC. The annual scientific production concerning each of the Scopus and WoS databases, during the period from 2010 to 2022, is shown in Figure 7. The compound annual growth rate is a business-specific term for the geometric progression ratio that provides a constant rate (in this context, of scientific production by both databases) over time.

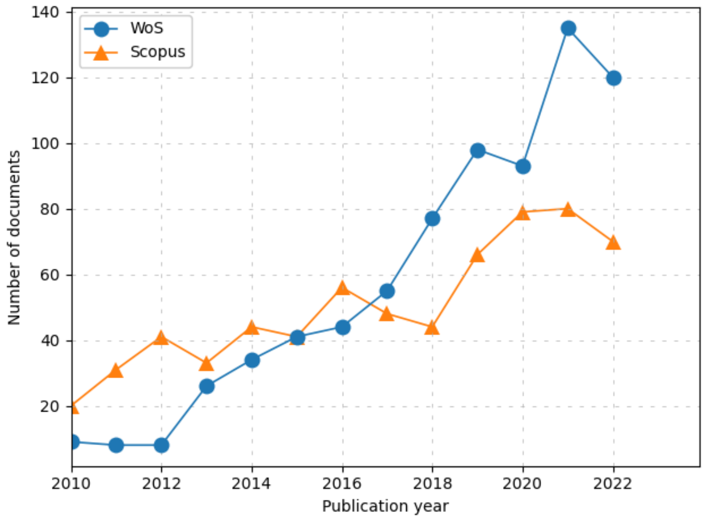

Figure 7: Annual scientific production related to databases.

It can be seen that till 2016, the number of documents published in the Scopus database is higher than that of WoS. However, the almost exponential increase in the number of documents published by WoS from 2016 to today is interesting. It is noteworthy that when applying the filter and removing duplicate papers, the vast majority of them were removed from the Scopus database (it happens randomly and automatically by the Scientopy tool), which may be interfering with the representation of the data in Figure 7.

After an initial pre-processing of the collected scientific production, the tool makes it possible to filter the publication by document type, as shown in Figure 8. The following figure includes the document types available and the results were refined to identify how many were article, conference paper, proceedings paper and review.

The vast majority of documents are articles, namely journal papers, followed by conference papers. It should be noted that since 2021 there has been a great increase in article-type publications, as shown in Figure 8. Furthermore, this analysis provides an idea of the degree of maturity of the technology/method applied to the problem, as journal articles are more mature.

On the other hand, the historical evolution of the different keywords was analyzed. Figure 9 shows the cumulative number of occurrences per year for each keyword. It is possible to verify that keywords, such as “Optimization”, “Healthcare”, “Scheduling” and “Home Health Care”, have a higher percentage of occurrence. In the same follow-up, keywords, such as “Simulation”, “Multi-objective Optimization”, “Vehicle Routing Problem”, “Genetic Algorithm”, and “Metaheuristics”, among others, have experienced sustained growth over the years, as they have supported the problem-solving approaches adopted by researchers. Note the growth of the keyword “Covid-19”, which since 2020, in addition to the epidemiological situation in the world, has contributed on a large scale to improvements

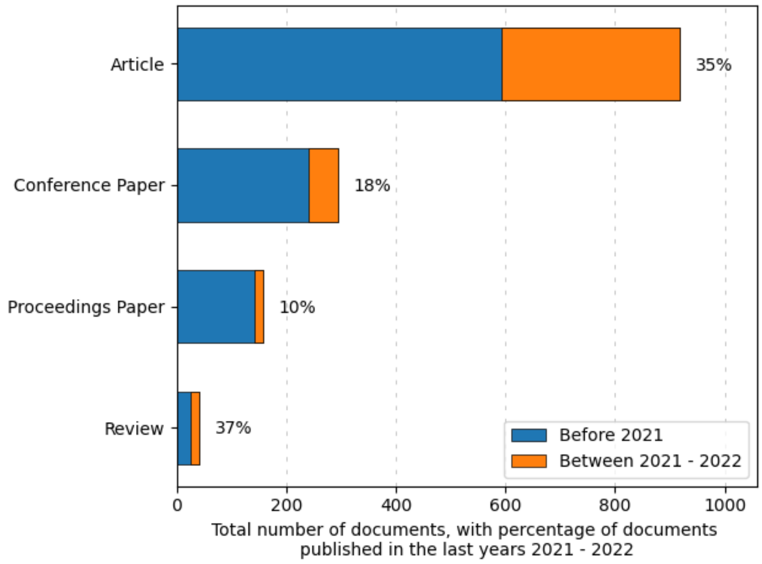

Figure 8: Document type in a bar trend graph.

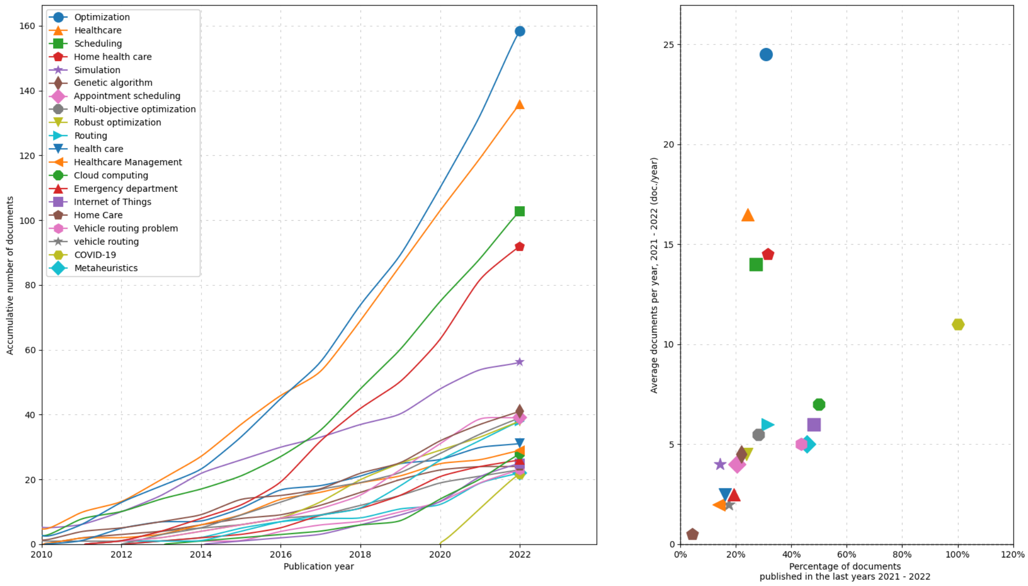

Figure 9: Historical evolution of cumulative occurrences by keyword.

in research in emergency processes and healthcare management. In addition, the keyword “Covid-19” also gave a boom in the development of smart applications with “Internet of Things” and using “Cloud Computing” applied to health.

With the ScientpPy tool, it was possible to extract the top countries that produce the most documents related to the main keywords. It is important to understand how the percentage per country is calculated in the ScientoPy tool, as this may depend on the configuration chosen by the user during the analysis. By default, the percentage of documents published by country is counted once for each country, i.e. an article with authors from 5 countries would be counted only once for each of those countries, or for example an article with 5 authors from the same country would be counted 5 times for that country. This is because each author is considered as a separate unit in the analysis. However, there is another configuration, which is to assign equal fractions to each country: in this case, an article with authors from 5 countries would be counted with 0.2 (or 20%) for each of these countries. In this sense, and since the default configuration is the most common option in many bibliometric analyses, this was used because it is easier to implement and understand the results. Furthermore, the default configuration has the advantage of being less error-prone. However, it is important to remember that the choice of calculation method can have a significant impact on the final results, and that the default option may have some limitations, such as the overvaluation of a country's scientific production.

Taking into account the above information, through a bar graph with trends, Figure 10 shows that the United States, China and France are the top 3, although Portugal appears in position 13 reveals the great growth of publications in HHC management. Note that if this analysis did not include the year 2022, Portugal would be in position 11 in terms of scientific contribution in these domains (as can be seen in the literature review of Alves et al., [7]). The orange bars represent the percentage of evolution relative to the number of documents in recent years, i.e.

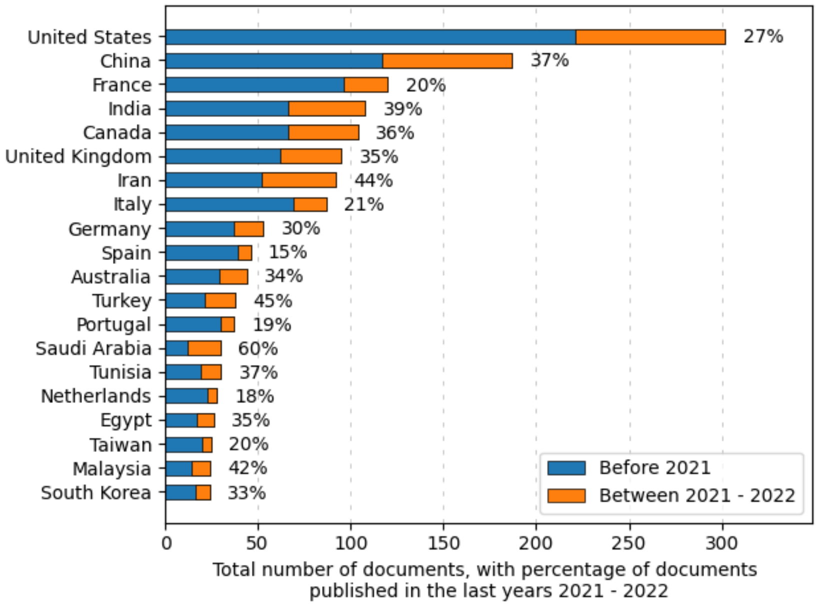

Figure 10: Historical document publication by country.

between 2021 and 2022. Therefore, from Figure 10, it is possible to verify the number of documents published in the last years (between 2021-2022), reflects a very representative margin of the growing research activity in HHC due to the pandemic situation.

Figure 11 shows the collaboration map between countries, allowing to identify the existing relationships in the globalized world. The network of interactions between each country is visible through the red lines. The countries colored in a darker blue are the ones that produce the most research and documents published on the HHC topic, validating the publication data in Figure 10. In turn, the representations of Figures 10 and 11 offer advantages of analysis and understanding of the scientific production in the areas of study. Some of the main advantages include visualization of results (clear and concise results to identify patterns), identification of most important countries and collaborations (funding opportunities and future collaboration) and identification of growth areas.

In general and in summary, the bibliometric analysis supports and demonstrates the significant impact of HHC

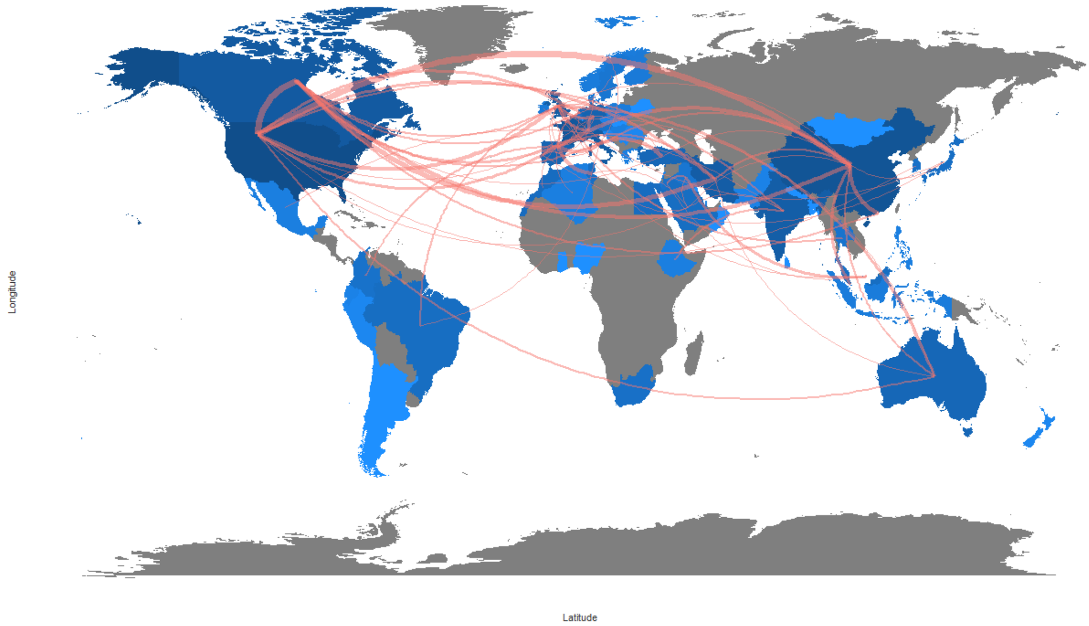

Figure 11: Country collaboration map.

on society, either at the level of primary care and social support or helping to manage route planning processes and scheduling problems of stakeholders in health organizations, research centers, universities, among other institutions.

2.3.3 Overview

Many of the works analyzed enhance research on HHC scheduling and routing problems and its operational planning process. Nevertheless, as shown in Figure 12, this problem covers a variety of applied research involving HHC organizations at three critical levels: strategic, tactical, and operational.

Most works and authors use real-life instances to validate their strategies and approaches, which is expected to continue in the future, with more and more private or public HHC service institutions wanting to improve their processes. Most OR problems are extensions of the VRP, with classical goals (such as travel costs) or constraints (such as periodicity, time windows, legislative rules, synchronization, etc).

From now on, a growth in health data is expected, as a consequence of inherent privacy, so the latest investigations in the HHC domain already recognize the need to increase and evolve procedures towards a more distributed level in terms of information management. With the increase of uncertainty constraints and real-time emergencies, new smart strategies and approaches will emerge, complementing the existing optimization techniques, which at this stage need greater automation and consequent digitalization of processes.

The concept of web and mobile applications in health (*mHealth* solutions) can be the next step for remote monitoring, digital tools and HHC visits made "online" (depending on the needs) [51]. On the other hand, AI, reactive programming can be complemented by already rich optimization methods, to improve the inclusion of dynamic aspects and unexpected events and to enhance greater sustainability and scalability for even more complex problems.

In summary, HHC is a promising and growing service where most of the home healthcare providers have historically not used OR tools in their daily operations, which represents opportunities to design smart, distributed and optimized applications [54].

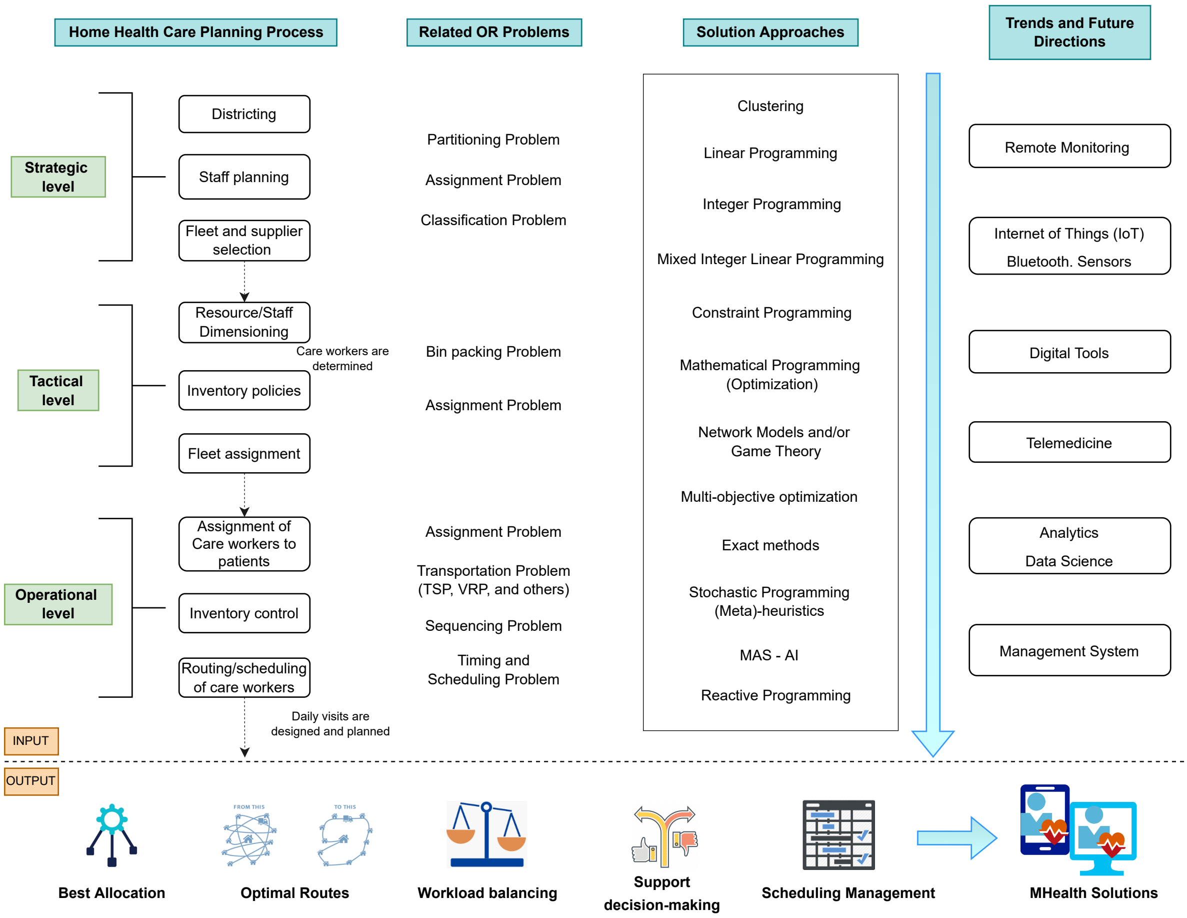

Figure 12: Overview of the past, present and future directions for HHC routing and scheduling. Adapted from [7].

2.4 Summary

This chapter discusses the results of the literature research conducted to answer the research questions and support the development of the proposed work. Thus, a review of the current state of the art associated with the logistical domains associated with scheduling and routing was presented, considering their different issues and solution methods. Furthermore, the routing and scheduling paradigms associated with the HHC service problem are introduced, considering all its characteristics, main constraints and main objectives.

As a complement, the related work in the literature was described and discussed, supported by a bibliometric analysis that mapped the main insights of the review and sought to contribute to a general overview of what the past was, what is in the present and what the future issues and future needs are in HHC scheduling and routing. In addition to supporting the work developed in this thesis, the results of the literature review also comprise a scientific contribution to the state of the art in this domain.

3

Models and Solution Methods

"An algorithm must be seen to be believed." - Donald Knuth.

This chapter aims to provide an essential basis on the scientific contribution. The main idea of this chapter is to discuss different perspectives on how to model and solve the main needs of the research questions, as well as to present the theoretical concepts of models and solutions methods. In an initial phase, the general formulation of the HHCSRP will be presented and described, taking into account its mathematical notation, objective functions and constraints. Furthermore, it is intended to formulate concepts, definitions, and background in the OR and AI areas and some of the most used strategies to solve the HHCSRP, namely the models and solution approaches used, and represent an integral part of the two main areas of knowledge, optimization and MAS.

3.1 Health Logistics and Problem Formulation

Logistics is already defined as supporting planning for managing material, services, information and capital flows, which progressively includes more complex information, communication and control systems required by today's business environment [50].

According to the previous chapters, HHC represents a wide range of health care services that can be provided in the homes of patients due to illness or injury. HHC is usually less expensive, more convenient, and just as effective as the care received in a hospital or skilled nursing facility. However, there is a need to efficiently and effectively plan, implement and control the direct and reverse flows of services (and materials) and all the associated information, from the point of origin to the point of service, in order to satisfy the requirements of providing health care to users.

The logistical management of health organizations involves making decisions taking into account the interdependence and coordination between functional areas and between organizations, guaranteeing quality in the provision of health care in a timely manner and with minimizing of costs. There are several aspects of a logistical nature to consider, whether in the health area or not, such as planning, prevention, transport, operating times, resources involved, reception conditions, reception, productivity of operations, management of materials, storage and dispatch, internal distribution of material, improvement of work strategies for health professionals and users beneficiary satisfaction, among others [50, 67].

All logistical operations must be designed in such a way as to be able to deliver, through multidisciplinary teams, the appropriate health services to the place where they are needed, distributing them to the right people, at the right time and at the minimum cost. Figure 13 presents the different dimensions of health logistics, with special emphasis on HHC.

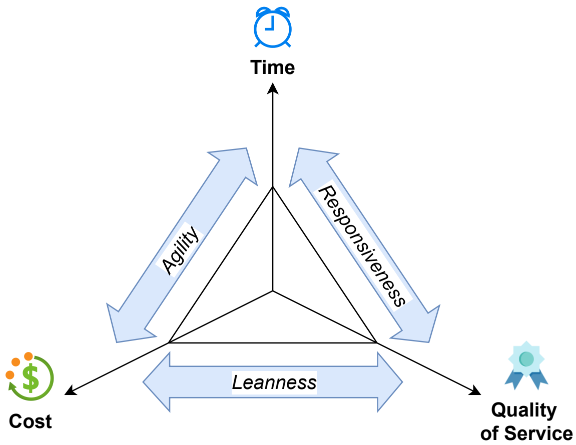

Figure 13: Dimensions of logistics management applied to Health. Adapted from Carvalho and Ramos [50].

The central dimensions of logistics management, with special attention to the provision of health care, are time, cost and quality of service. However, a good balance between time and cost is necessary to develop the agility variable. A good combination of cost and service quality develops the leanness variable. A good combination of time and service quality develops the responsiveness variable.

In this scenario, the intervention of health entities has been an added value, mainly in terms of primary health care and home visits. However, home health services urgently need computational support and modernization in their operation, as they are often manually managed, lacking digital resources that could provide the expansion of support coverage to users, in addition to minimizing the deficit between resources and requirements, supplying thus the inefficiencies in the planning horizon process, constraints (times, available resources, among others) management decisions and information services. Thus, the problem arises when it is necessary to overcome the difficulties that these services entail, difficulties such as excessive delay in routes that could be reduced, poorly formulated planning and without viable replacement options and, consequently, the costs involved [75].

In any case, it is necessary to be aware that the patient is the central element of health management and one cannot want to minimize everything and everyone without guaranteeing the quality of service. Hence the need for an integrated view of the general functioning, where the Health Unit is inserted, in an attempt to optimize or develop computational and intelligent systems consciously, in this case, the provision of care at home.

The description of the general model proposed in this thesis aims to support the planning of routes and schedules of health professionals within the HHC sector, namely in the context of health and/or social services in Bragança, Portugal. It should be noted that, despite the concrete application of the study, the model can be replicated in other institutions and cities. Based on the previous context, this planning should follow different objectives and consider several key constraints inherent to this context. The notation used for the model formulation is presented below, together with the mathematical formulation of the objectives, parameters, assumptions and key constraints of the model.

3.1.1 Notation

The notation will be represented by indices and sets, parameters, assumptions, and key variables that will be an integral part of the mathematical model to be formulated.

Consider a routing and scheduling network $G = (N, A)$ with nodes $N = \{0, 1, 2, \ldots, \mathrm{n}\}$, where node 0 is the healthcare unit and the others are patient locations, and $A = \{(i, j) : i, j \in N,\ i \neq j\}$ is the set of routes. Each node in the network G represents a patient location (a visit in the context of HHCSRP), and two dummy nodes 0 and $n + 1$ have been added to represent the depot (HHC entity). The model integrates other entities, such as vehicles, k, representing the means of transportation for the healthcare team. Resources can be defined by a set $K = \{1, \ldots, \mathrm{k}\}$, representing the vehicles/teams available.

Furthermore, a set $PD = \{1, \ldots, \mathrm{pd}\}$ was created, representing the pd periods of the day (morning, lunch or afternoon views), allowing the planning of visits at times desired by the patients.

Last but not least, the set $P = \{1, \ldots, \mathrm{p}\}$ was created to index the list of involved patients, along with the set $T = \{1, \ldots, \mathrm{t}\}$ which takes into account the list of different services (treatments or care) that patients need.

Table 3 summarizes the sets that will be considered in the formulation of the problem.

Table 3: Sets description.

Sets	**Description**
N	list of nodes (including depot and all patients locations)
P	list of patients
T	list of treatments
K	list of vehicles/teams
PD	list of periods of the day

An instance of the problem is defined by the following parameters:

- M_{Qt} is the maximum daily work time for each vehicle (maximum shift duration);
- M_{Qd} is the maximum daily work distance for each vehicle (limited distance per day);
- F_{pd} is the maximum duration of each period of the day (e.g. morning, lunch, or afternoon);
- $c_{ij} \in C$ represents the duration of the trip between location i and location j, and C is the time matrix between the n locations (in minutes);
- Each arc $(i, j) \in A$ represents a potential link between two patients and represents the travel time from location i to location j, with an associated cost c_{ij};
- $d_{ij} \in D$ represents the distance between location i and location j, and D is the distance matrix between the n locations (in kilometers);
- Each arc $(i, j) \in A$ has associated a given distance d_{ij} cost. This cost is equivalent to a distance cost (kilometers) from location i to location j;
- q_t is the parameter that defines an average execution time for each treatment or duration of care, for $t \in T$;

In addition, an instance of the problem may also consider the following assumptions:

- a route should start and end at the depot $\{0\}$;
- the patient's profile is known;
- to ensure that all patients assigned to a working day are covered, all patients admitted for home care visits must be assigned to a group of health professionals, or vehicles;
- in general, only one health professional is assigned to each vehicle;
- the times and distances between locations are based on Google Maps Application Programming Interface (API).

A VRP problem like the one addressed in this thesis needs to be enabled with different variants (periodicity, preferences, synchronization, among others). Therefore, some variables related to the sequence in which nodes are visited, demands of patients in terms of visit patterns (e.g., 3 visits per week with interspersed days), and other specific variables must be defined (as shown in Table 4).

Table 4: Definition of variables.

Variables	Definition
x_{ij}^k	Binary variable that equals 1 if vehicle k travels between nodes i and j; and zero otherwise
v_k	Binary variable that equals 1 if vehicle k is used; and zero otherwise
e_k	Maximum time, in minutes, that a vehicle k can be used per day
m_{ij}^k	Number of patients served in location j by vehicle k, with this vehicle traveling from location i
u_i^k	Decision variable used to eliminate subtours involving the place in the visit sequence of vehicle k for the location i
w_{ik}	Decision variable: equal to 1 if patient $i \in P$ can be visited by vehicle k (matching between treatment requested and health professional skill); 0 otherwise
y_{ij}^k	Real variable, used to quantify the time spent on travel and patient treatment to travel from location i to location j by vehicle k
z_{ij}^k	Real variable, used to quantify the distance traveled from location i to location j by vehicle k

Therefore, a customized VRP model (with some variants), with sets, parameters, and variables, may represent some of the main characteristics inherent in the current problems of HHC organizations.

3.1.2 Objective Functions

Depending on the planning and management circumstances (organizations, days, etc.), the objectives to be considered may differ.

As noted above, minimizing or optimizing costs plays a key role in this sector, and such costs can be measured in monetary terms, distance, or time traveled. In this study, a key objective to be considered is the minimization of travel costs, with costs measured in different ways.

1. Minimization of total costs, in terms of time or distance traveled (Equation (3.1)) - as a result, the number of patients served per vehicle will increase. It should be noted that Equation (3.1) does not take into account

the time spent providing care to patients at home because it is assumed that this time is the same for all patients and, therefore, will not have an effect on planning decisions.

$$\min f_1 \equiv \sum_{i \in N} \sum_{j \in N} c_{ij} \left(\sum_{k \in K} x_{ij}^k \right) \tag{3.1}$$

2. Minimizing costs in monetary terms by reducing the number of vehicles required to visit patients' homes, if possible, and respecting constraints (Equation (3.2); with the number of vehicles serving as a proxy for investment costs) - this is essential from a management and investment planning perspective, as it provides information on the resources required to meet HHC demand. In addition, it allows searching for solutions with better workload balancing between the available teams and vehicles.

$$\min f_2 \equiv \sum_{k \in K} v_k \tag{3.2}$$

3. In a multiple-criteria decision analysis, and still within the context of budget cuts in HHC, it may be relevant to support decision-making using a multi-objective approach. The idea is to minimize different conflicting objective functions (e.g., two or more) and assist the decision-maker in the management of health planning (Equation (3.6)).

$$\text{Tmax} = \max_{i \in N, k \in K} y_{i0}^k \tag{3.3}$$

$$\text{Kmmax} = \max_{i \in N, k \in K} z_{i0}^k \tag{3.4}$$

$$\text{Cmax} = \sum_{i \in N} \sum_{k \in K} x_{ij}^k \tag{3.5}$$

$$\textbf{Min} \left\{ \text{Tmax, Kmmax, Cmax} \right\} \tag{3.6}$$

Tmax in (3.3) is the maximum value of the total amount of time spent by the caregivers (health professionals), Kmmax in (3.4) is the maximum value of the total amount of distance traveled by the vehicles and Cmax in (3.5) is the number of vehicles used, among those available.

3.1.3 Constraints

Depending on the model to be used, a different set of constraints can be considered, described below.

Route-related constraints

Constraints (3.7) make sure that all vehicles start at the depot, while (3.8) ensure that all vehicles arrive at the depot.

$$\sum_{i \in N} x_{0i}^k = 1, \qquad \forall k \in K \tag{3.7}$$

$$\sum_{i \in N} x_{i0}^k = 1, \quad \forall k \in K \tag{3.8}$$

On the other hand, the constraints (3.9)-(3.10) state that each patient is visited exactly once and by only one vehicle, respectively.

$$\sum_{i \in N} \sum_{k \in K} x_{ij}^k = 1, \quad \forall j \in N \tag{3.9}$$

$$\sum_{j \in N} \sum_{k \in K} x_{ji}^k = 1, \quad \forall i \in N \tag{3.10}$$

Equations (3.11) ensure that a vehicle that enters a location j must also leave from it, ensuring the continuity of the route.

$$\sum_{i \in L} x_{ij}^k = \sum_{i \in L} x_{ji}^k, \quad \forall j \in N, \ \forall k \in K \tag{3.11}$$

Equation (3.12) eliminates the routes between the same node.

$$x_{jj}^k = 0, \quad \forall j \in N; \forall k \in K; \tag{3.12}$$

On the other hand, equations (3.13) prevent subtours between the locations and the depot (sub-circuit elimination constraints) by ensuring that the solution contains no cycles disconnected from the depot (where M is a penalty parameter - large number) [145].

$$u_j^k \geq u_i^k - M(1 - x_{ij}^k) + 1, \quad \forall i, j \in N; \forall k \in K; i \neq j \tag{3.13}$$

Finally, constraints (3.14) and (3.15) are flow conservation equations and ensure that the flow on each arc accumulates trips, service times and distances from all previous visits on a route. The parameter q_t is the treatment time associated with the patient to be visited.

$$\sum_{i \in N} y_{ji}^k - \sum_{i \in N} y_{ij}^k = \sum_{i \in N} x_{ji}^k \left(c_{ji} + q_t\right), \quad \forall j \in N, \ \forall k \in K \tag{3.14}$$

$$\sum_{i \in N} z_{ji}^k - \sum_{i \in N} z_{ij}^k = \sum_{i \in N} x_{ji}^k \left(d_{ji} + q_t\right), \quad \forall j \in N, \ \forall k \in K \tag{3.15}$$

Service level-related constraints

Constraints (3.16) and (3.17) impose an upper bound on the flow in the arcs.

$$y_{ij}^k \leq M_{Qt} \, x_{ji}^k, \quad \forall i \in N, \ \forall j \in N, \forall k \in K \tag{3.16}$$

$$z_{ij}^k \leq M_{Qd} \, x_{ji}^k, \quad \forall i \in N, \ \forall j \in N, \forall k \in K \tag{3.17}$$

On the other hand, constraints (3.18) and (3.19) initialize the flow in the arc from the depot to the first patient to be equal to the travel time and the distance traveled.

$$y^k_{0i} = x^k_{0i}\, c_{0i}, \qquad \forall i \in N,\ \forall k \in K \tag{3.18}$$

$$z^k_{0i} = x^k_{0i}\, d_{0i}, \qquad \forall i \in N,\ \forall k \in K \tag{3.19}$$

Patient preference-related constraints

Finally, constraints (3.20) ensure that every patient is visited by a specific vehicle (synchronization of requested care and nurses (care workers) skills), according to the compatibility coefficients.

$$\sum_{i \in N} x^k_{ij} \leq w_{jk}, \qquad \forall j \in N,\ \forall k \in K \tag{3.20}$$

Several variables will be bounded and set to zero by constraints (3.20) if the compatibility matrix between patients and vehicles is too strict, removing the variables from the formulation.

Additionally, the health organization assigns only one health professional to each vehicle, taking into account the skills and route (it can be your personal vehicle or not). These constraints are related to the limitations imposed by the organization to guarantee the viability of the service without overloading other activities.

Vehicle-related constraints

Equation (3.21) defines the maximum visit time per vehicle and ensures that each vehicle has enough time to travel between the nodes (route), serve their patients and return to the depot within the regulated daily work time, represented by the variable e_k.

$$e_k \equiv M_{Qt} - \sum_{i \in N} \sum_{j \in N} c_{ij}\, x^k_{ij}, \qquad \forall k \in K; j \neq i \tag{3.21}$$

Equation (3.22) defines the maximum visit time per vehicle.

$$\sum_{i \in N} \sum_{j \in N} m^k_{ij}\, q_t \leq e_k, \qquad \forall k \in K; j \neq i \tag{3.22}$$

Furthermore, Equation (3.23) ensures that each vehicle cannot be used for a number of hours higher than the regulated daily work time - and this includes the time used for travel (first term) and the time devoted to care provision (second term). Similarly, Equation (3.24) ensures that the time available per period of the day cannot be exceeded.

$$\sum_{i \in N} \sum_{j \in N} c_{ij}\, x^k_{ij} + \sum_{i \in N} \sum_{j \in N} m^k_{ij}\, q_t \leq M_{Qt}, \qquad \forall k \in K; j \neq i \tag{3.23}$$

$$\sum_{i \in N} \sum_{j \in N} c_{ij}\, x^k_{ij} + \sum_{i \in N} \sum_{j \in N} m^k_{ij}\, q_t \leq F_{pd}, \qquad \forall k \in K, j \neq i \tag{3.24}$$

Equation (3.25) defines the maximum number of vehicles that can be used.

$$\sum_{k \in K} v_k \leq K \tag{3.25}$$

Finally, Equation (3.26) can be used if it is necessary to impose the use of each vehicle, even if it is only for one visit.

$$v_k \geq x_{ij}^k, \qquad \forall i \in N, \forall j \in N, \forall k \in K \tag{3.26}$$

3.1.4 Variables

Non-negativity conditions are given by Equations (3.27) and (3.28).

$$m_{ij}^k \geq 0, \qquad \forall i, j \in N; \forall k \in K; \tag{3.27}$$

$$e_k \geq 0, \qquad \forall k \in K \tag{3.28}$$

On the other hand, binary variables are given by Equation (3.29) and (3.30). These equations specify the domain of the decision variables. Furthermore, (3.31) and (3.32) define the lower bounds on the variables.

$$v_k \in \{0, 1\}, \qquad \forall k \in K \tag{3.29}$$

$$x_{ij}^k \in \{0, 1\}, \qquad \forall i, j \in N; \forall k \in K \tag{3.30}$$

$$y_{ij}^k \geq 0, \qquad \forall i \in N,\ \forall j \in N,\ \forall k \in K \tag{3.31}$$

$$z_{ij}^k \geq 0, \qquad \forall i \in N,\ \forall j \in N,\ \forall k \in K \tag{3.32}$$

The cost of patient visits in the proposed mathematical model is independent of the vehicles used to carry them out, but does not take into account the requirement to ensure that each patient is visited by a qualified healthcare provider (taking into account the required care and/or preferences), according to the compatibility coefficients and according to the transport of an available or assigned vehicle. In certain situations, two caregivers may be needed during one visit in the HHCSRP environment, such as assisting a heavy patient out of bed or performing cleaning activities. This circumstance can be described as two visits, i and j, coupled with a precedence constraint. Other elements to think about can include time windows, continuity of care, and/or monitoring of unforeseen emergencies.

Given the mathematical modeling presented and to guide and support operational planning, there are several promising methods belonging to deterministic and stochastic classes that can solve the HHC problem. In summary, all notation (sets, parameters, variables), objective functions and all the diversity of constraints, can be viewed as an integer linear optimization problem where patient visits are scheduled and routes are designed for the various days of the time horizon, patient preferences and/or considering multi-objectives, in order to reduce costs for all routes with promotion of a better workload-balancing.

3.2 Optimization

Optimization problems arise in many areas, from industry to services, and health, among others. An optimization problem can be represented as a minimization or maximization problem. Therefore, the main goal of the optimization is to find the optimal solution, if possible, that either minimizes or maximizes the objective function, from a set of feasible solutions [31]. However, finding the optimal solution is a difficult task.

In this thesis, the optimization problem is presented as a minimization problem, which is also generally the most widely used.

Thus, for a set of feasible solutions X, the goal of a minimization problem is to find x^* such that:

$$f(x^*) \leq f(x) \;\; \forall \;\; x \in X \tag{3.33}$$

The function $f(x)$ is called the objective function. In turn, the objective function can represent any parameter (such as time, cost, size, etc.) that needs to be optimized.

The variable x associated with the function $f(x)$ is called a design variable or decision variable [27]. Generally, optimization problems may contain a set of decision variables. For example, the variable x is therefore represented as a vector with a set of decision variables, $x = [x_1, x_2, ..., x_n]$, and these variables are located around the "solution space". In this context, it is important to mention that, the decision variables can be either continuous, integer, binary or discrete.

In any optimization problem (assuming the objective function is to be minimized), two types of solution values can be achieved: the local minimum or the global minimum. A local minimum of a function is a point where the function value is smaller than at nearby points, but possibly greater than at a distant point. A global minimum is a point where the function value is smaller than at all other feasible points. According to Thomas Weise [205] the definition of local and global minimum is given as follows.

Definition 1. *Function f has a minimum (or local minimum) over set X at x^* if there exists $\delta > 0$ such that $f(x^*) \leq f(x)$ for all $x \in X$ and $\|x - x^*\| < \delta$.*

Definition 2. *Function f has a global minimum over set X at x^* if $f(x^*) \leq f(x)$ for all $x \in X$.*

For instance, the global minimum is the lowest value (solution) among all the feasible solutions. In turn, the local minimum is the lowest value among the neighboring values at a distance δ. In this sense, Figure 14 illustrates an example of local and global minimum for a given function $f(x)$. On the other hand, for a given objective function $f(x)$, an optimization problem can have multiple local optima with identical objective function value. The latter is called multimodal problem.

Several examples of real optimization cases contain constraints on the variables. Generally, the constraints set conditions for the variables that are required to be satisfied. The constraints define a search space, also known as feasible region within which the solution must be enclosed.

In terms of the number of objective functions, optimization problems can be classified as single objective or multi-objective. In multi-objective optimization, the optimization problem involve multiple, conflicting objectives. The multi-objective optimization process extends the optimization theory by allowing single objectives to be optimized simultaneously [60]. The multi-objective problems can be addressed by optimizing all objectives simultaneously

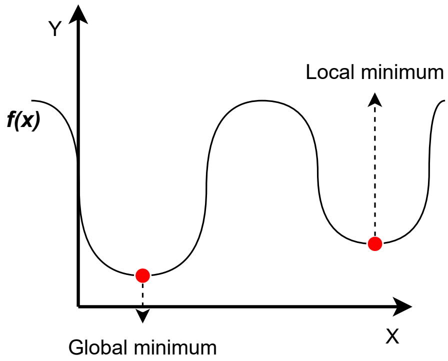

Figure 14: Local and global minimum of $f(x)$.

or aggregating the objectives into a scalar function and solving the resulting single-objective optimization problem. Both approaches focus on finding a set of optimal trade-offs, the so called Pareto-optimal set.

3.2.1 Optimization Methods

Classifying an optimization problem is a complex issue, but finding the optimal solution is a difficult task [200]. The next subsections will discuss some (the most commonly used) optimization approaches in more detail.

There are some optimization problems that have been exhaustively studied over the years in the literature where specific techniques and algorithms, such as linear programming, mixed integer programming or (meta-)heuristics algorithms, have been applied to solve them [188]. One of the most common applications using this type of optimization methods is solving various planning and scheduling problems.

This research project considered the scheduling and routing problem in HHC taking into account different objectives (time/distance, workload balancing, preferences, periodicity, among others) to be optimized individually or simultaneously (multi-objective approach). Furthermore, the problem of HHCSRP is extended to the use of hybrid methods, namely the union and/or combination of strategies or algorithms aiming to generate better results.

Figure 15 presents a brief summary classification of the main optimization methods and algorithms. It should be noted that the same classification could be further extended with multi-objective strategies (using algorithms such as NSGA-II) and even with the interconnection of different combined optimization methods, called hybrid strategies.

The figure presents some of the methods that appear differentiated by the blue color (exact approaches) and the orange color (approximate approaches). The methods that were explored, implemented and coded within the scope of this research project have been identified in bold. Other methods, such as those of single solution, are shown in bold because they were also used and applied via open-source optimization tools that already have implemented them. Typically, scheduling or routing problems are large and cannot be accurately solved in an acceptable amount of time, so practitioners frequently prefer to employ some of these methods due to the NP-hardness of the majority of scheduling problems. The methods are described in the next subsections.

3.2.2 Exact Methods

Exact algorithms are a subset of deterministic optimization techniques. They are also known as non-heuristic or complete algorithms [152]. For small instances, researchers usually use exact methods. Due to their deterministic mechanism, exact methods can be found to solve many optimization problems, single or multi-objective optimization

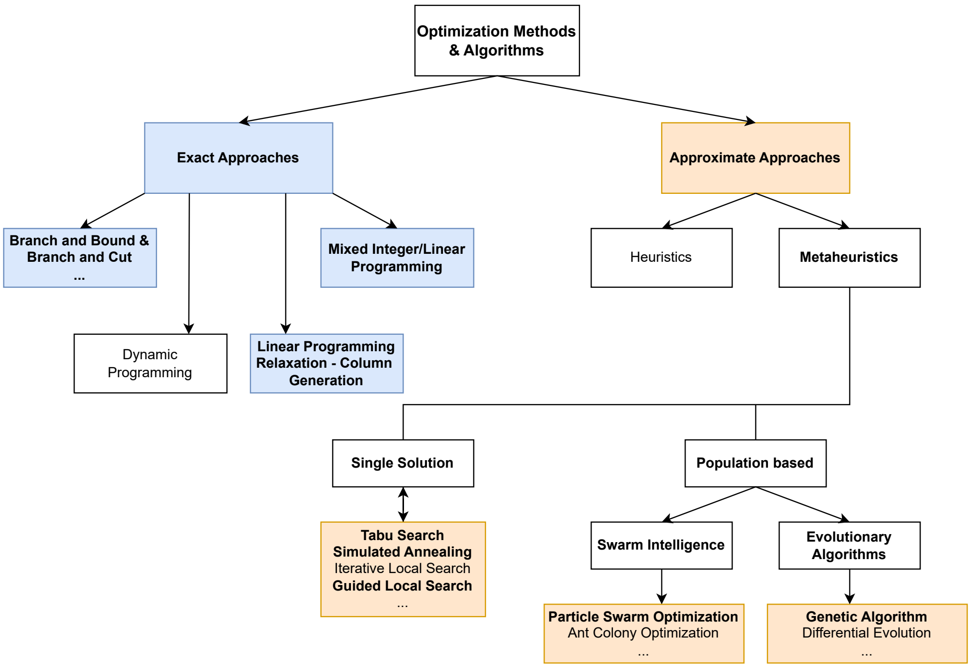

Figure 15: Brief classification of optimization methods and algorithms.

problems. Usually, an exact optimization method is one that after a certain number of iterations finds the exact solution. That is, a method that solves an optimization problem with an effort that grows polynomially with the size of the problem. The situation is different if problems are NP-hard, as exact optimization methods need exponential effort. Furthermore, with a predictable amount of resources, such as function evaluations or computation time, exact algorithms are guaranteed to discover a optimum [91, 152]. Well-Known exact algorithms are based on the branching principle, i.e., splitting a known problem into smaller sub-problems, where each can be solved and assess its optimality. The Branch and Bound (BB) paradigm is an example of exact algorithms [123]. In practice, most combinatorial optimization problems can be formulated as MILP, where BB or integer programming are the exact methods of choice. A mixed integer programming problem may contain both integer and continuous variables and the objective function and constraints are linear functions, then the problem is termed a MILP [90]. Integer variables may be restricted to the values 0 (zero) and 1 (one), in which case they are referred to as binary variables. Or they may take on any integer values, in which case they are referred to as general integer variables. Thus, MILP models are often used for system analysis and optimization, as they present a flexible and powerful method for solving large and more complex problems. On the other hand, the BB method is based on an intelligent enumeration of the solutions that are candidates to be integer optimal by successively partitioning the solution space and cutting the search tree considering the bounds calculated during the enumeration [94].

In summary, some well-known exact methods are BB, branch-and-cut, branch-and-price, dynamic programming, linear programming relaxation and MILP. Nowadays, the exact methods are easily applied using powerful, practical and general-purpose commercial tools such as CPLEX or Gurobi. However, for many problems, the size of the practically solvable instances is rather limited. The memory consumption of exact algorithms can be very large, limiting the resources and, in turn, the pplications [79].

CG is a classical technique to solve large and complex problems, such as linear or integer problems. Typically, only a small fraction of the variables is needed to prove optimality which makes the technique interesting for problems with a huge number of variables. Thus, in this method it is crucial to start by solving a mathematical program iteratively adding the variables of the model [68].

In general terms, CG is a strategy that starts with a small, manageable part of a problem (specifically, a few variables), solving that part, analyzing that partial solution to discover the next part of the problem (specifically, one or more variables) to add to the model, and then solve the extended model. In CG this process is repeated until a satisfactory solution to the problem is obtained. In formal terms, CG is a way to solve a programming problem by generating and adding columns, corresponding to constrained variables in its dual formulation. In the dual formulation glsCG acts as a cutting plane method. The main advantage of CG is the fact that not all possibilities need to be enumerated. Instead, the problem is formulated as a Restricted Master Problem (RMP). This RMP has as few variables as possible, and new variables are brought into the basis as needed, similar to the simplex method, if a column with a negative reduced cost can be found, it is added to the RMP and this process is repeated until no more columns can be added to the RMP. Figure 16shoes the basic procedure of the CG strategy.

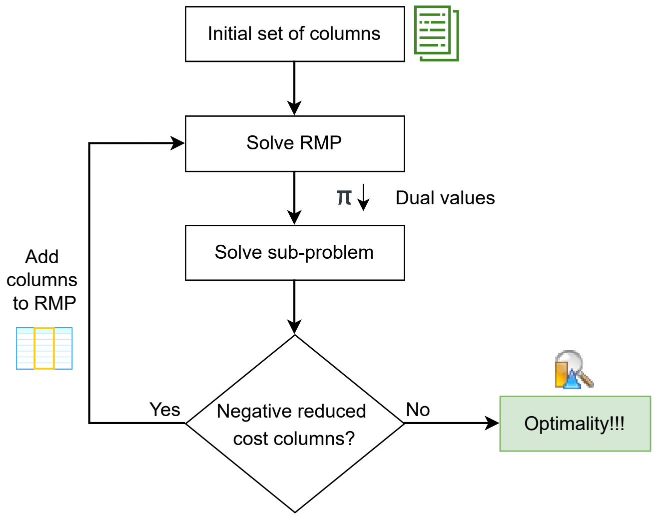

Figure 16: Flowchart of column generation procedure.

In this context, many researchers have observed that CG is a very powerful technique for solving a wide range of industrial problems to optimality or to near optimality. Ford and Fulkerson, for example, suggested CG in the context of a multi-commodity network flow problem as early as 1958 in the journal of Management Science [92]. By 1960, Dantzig and Wolfe had adapted it to linear programming problems with a decomposed structure [58]. Gilmore and Gomory then demonstrated its effectiveness in a cutting stock problem [98]. More recently, vehicle routing, crew scheduling, and other integer-constrained problems have motivated further research into CG [159].

3.2.3 (Meta-)Heuristics

When instances become too large and cannot be solved (or cannot be solved in polynomial time) by exact methods, heuristics and in particular, metaheuristics are often used. If optimal solutions cannot be computed efficiently in practice, approximate algorithms are usually used to find very good solutions in a reasonably short time.

Heuristics and meta-heuristics are well-established solution methods in contemporary computer-aided optimization. Although they present solutions that are not always optimal, their wide applicability and ability to quickly obtain good solutions make them incredibly attractive for applied optimization.

Heuristics can be defined as problem-solving methods that are based on practical experience and knowledge, which are developed or adapted to the particularities of a specific optimization problem or problem instance [209]. “Classical” heuristics, refer to methods that, at each step, always advance from an existing solution to one that is better in the surrounding area, ending when there is no possibility of improving the solution. Traditional heuristics naturally fall into two categories: constructive heuristics (e.g., savings algorithm) and improvement heuristics [121].

Metaheuristics can be defined as an approach method that does not rely on the type of the problem, which through general-purpose optimization strategies, will be able to generate single-solution based procedures (local search) and mechanisms based on population (random search). Over the past years, research on the use of nature-inspired metaheuristics has been increasingly appreciated. They are applicable to a wide variety of problems and problem cases. The term “meta” refers to the higher-level general technique used to direct the underlying heuristic strategy, with a focus on finding high-quality solutions quickly [78, 191]. For this reason, it was chosen to use metaheuristics in the contribution of this work, namely because they have a more sophisticated and robust programming inspired by the intelligent behavior of natural systems (e.g., GA and PSO). Furthermore, the use of metaheuristics is an attractive approach to reduce computation time while still producing solutions that are close to optimal, given the complexity of HHCSRP and the fact that solving the problem accurately can take a long time for large instances [189].

3.2.3.1 Genetic Algorithm

The GA algorithm is a population-based algorithm inspired by Charles Darwin’s theory of natural evolution, developed by Holland [113]. This algorithm reflects the process of natural selection where the fittest individuals are selected for reproduction in order to produce offspring of the next generation. GA has been applied in many optimization problems and implemented in many optimization and machine learning applications [99].

GA has an important feature that is it does not require any gradient information for the objective function [109]. Each member called an individual in the population is represented as a chromosome. In terms of encodings for chromosome it is possible to generate different representations for the GA algorithm, but originally, each individual is encoded as a binary to represent chromosome. Candidate solutions are evolved to find better solutions through the three GA operators: selection, crossover, and mutation.

The evolution in GA usually begins with a random generation of the population, and at each iteration (called generation), selection, crossover, and mutation operators are applied to the population. In the selection procedure, the fittest (better) individuals are selected for reproduction, where the fitness of each individual represents the objective function value. This phase ensures that the best individuals with high-quality characteristics (chromosomes) are selected for the next generation. At the end of the selection procedure, the mating pool is created, which contains the best individuals. In the crossover procedure, two individuals are selected from the mating pool. In this stage, both individuals exchange their chromosomes for creating offspring. The new offspring are added to the population. Later, in the mutation phase, the position of a given gene in the chromosome is randomly selected and subjected to a mutation with a low random probability. This implies that some of the bits in the bit string can be flipped. It should be noted that, mutation occurs to maintain diversity within the population and prevent premature convergence. Therefore, the last two procedures, crossover and mutation are operators that ensure that high-quality genes are transmitted and reproduced within the population.

In the GA, this process is repeated until a predefined termination condition is reached, such as a maximum number of generations (iterations), maximum number of function evaluations, or no further improvement has been noticed for a certain number of generations. The GA pseudocode algorithm is described in Algorithm 1, as an example of its sequence of actions.

Algorithm 1 The pseudocode of GA

```
Initialize population randomly
Evaluate the fitness value
Select fittest individuals
while stop criterion not reached do
    Crossover operation
    Mutation operation
    Evaluate the fitness value
    Select fittest individuals
end while
```

Regarding the selection procedure, at the end of each successive generation, part of the population is selected for reproduction (crossover and mutation) to generate the next generations. There are different selection methods described in the literature, but in this project, the selection process based on elitism was used and will be described. The elitism enables the continuous exploiting of promising areas. Thus, instead of replacing the entire population, some parents are preserved and carried to the next generation.

After the selection procedure, the crossover operation is triggered. From the mating pool, two parents are randomly selected, and the segments from each parent are exchanged to produce offspring. In terms of the most used crossover techniques, single-point, two-point and uniform crossover mechanisms are mentioned in the literature as commonly used in the GA [119]. The uniform crossover is a gene-based operator, where each gene in one parent is exchanged with the corresponding gene from the other parent with respect to a predefined probability [146].

Finally, in the mutation procedure, the operation is based on inverting each offspring's bit based on a small probability, called mutation rate. Thus, a random number is generated for each bit, and if the random number is less than the mutation rate, then the mutation is performed. In this way, the mutation rate in GA serves to maintain the diversity of the population (exploration), thereby, the algorithm is able to explore other areas in the solution space. It is also important to note that the mutation rate is problem-dependent, i.e., the value might work differently depending on the characteristics of the optimization problem. On the one hand, a very high mutation rate may disrupt the population, while a very low mutation rate is not preferred also, as the population may not be able to jump out of the optimum local region. Hence, the mutation rate has to be determined carefully. In the literature, some authors refer to a preference for fixed mutation rates, and others already mention that a dynamic mutation rate is more effective, that is, starting with a high mutation rate and gradually decreasing it over time in the optimization process [108].

3.2.3.2 Particle Swarm Optimization

PSO was introduced by Kennedy and Eberhart [116], characterized by being a stochastic population-based optimization technique based on the movement and intelligence of swarms. In contrast to the evolutionary algorithms, such as the GA, the algorithm mimics the "intelligent" behavior in a swarm, such as "birds flocking".

The concept of social interaction between individuals by exchanging information within the population is used to solve optimization problems. Therefore, in the PSO algorithm, usually, each single solution is a "bird" in the search space, called a particle, and a set of particles form a *swarm*. All of particles have fitness values which are evaluated by the fitness function to be optimized, and have velocities which direct the flying of the particles. Relying on their own best experience (designed *pbest*) and the best experience of the swarm (called *gbest*), the particles "fly" in the search space looking for regions with potentially high-quality solutions. In this sense, for a given problem, each particle in the swarm represents a candidate solution.

Another important feature of the PSO algorithm is that it does not require any gradient information of the objective function. Furthermore, the PSO algorithm has been, over the years, applied to many optimization problems in different domains [166, 179].

In mathematical terms, the formulation of the PSO algorithm can be described considering a D-dimensional search space, where the i^{th} particle can be represented as a D-dimensional vector, $x_i \in \mathbb{R}^d$.

Considering this notation, the velocity of the particle i^{th} is calculated to determine the direction and the distance that each particle should move in the search space, using the following equations [202]:

$$v_{i+1} = v_i + c_1\, r_1(pbest_i - x_i) + c_2\, r_2(gbest - x_i) \tag{3.34}$$

the position of the particle i^{th} is given by:

$$x_{i+1} = x_i + v_{i+1} \tag{3.35}$$

where v_i and x_i are the velocity and the position of the i^{th} particle, respectively, and v_{i+1} and x_{i+1} are the corresponding velocity and position in the next instance of time. Moreover, $pbest_i$ denotes the best position (solution) of the i^{th} particle, and $gbest$ is the best position in the *swarm*. Furthermore, r_1 and r_2 are independent random numbers generated within the range $[0, 1]$. In this way, c_1 and c_2 are acceleration coefficients that determine the stochastic acceleration towards *pbest* and *gbest*, respectively. From the equations (3.34) and (3.35), c_1 adjusts the maximum step size toward the best particle in the *swarm* and c_2 adjusts the maximum step size towards the personal best position of particle i.

In summary, the PSO pseudocode algorithm is described in Algorithm 2, as a standard example of its sequence of actions.

Algorithm 2 The pseudocode of PSO

```
Initialize parameters
Initialize population
for each particle do
    Evaluate (fitness)
    Update pbest, gbest
end for
while stop criterion is not reached do
    for each particle do
        Update velocity and position
        Evaluate (fitness)
        Update pbest, gbest
    end for
end while
```

3.2.4 Multi-objective Optimization

Several real optimization problems are formulated as Multi-objective Optimization (MOO) problems, with several conflicting objectives to be optimized simultaneously. In the context of MOO, the notion of an "optimum" solution may not be just for one objective but rather for more than one objective [60]. Therefore, the optimal solution to the problem, rather than a single solution, a set of solutions to two or more objectives, defining the Pareto front [59].

Considering a MOO problem with k objectives and n decision variables can be formulated as follows:

$$\min_{x \in X} f(x) \equiv [f_1(x), f_2(x), f_3(x), \ldots, f_k(x)] \tag{3.36}$$

where $f(x)$ is a vector with k objective functions to be optimized, and the set X is the feasible set of decision vectors, i.e., $x \in X \subseteq \mathbb{R}^n$, but it depends on the n-dimensional application domain.

It is important to mention that it is not easy to deal with multi-objective problems because in MOO, there does not typically exist a feasible solution that minimizes all objective functions simultaneously. Therefore, attention is paid to Pareto optimal solutions, that is, solutions that cannot be improved in any of the objectives without degrading at least one of the other objectives (trade-off). To deal with trade-off solutions, the notion known as the Pareto Optimally is commonly used in the literature [55].

Solutions are compared in terms of Pareto dominance, that is, a solution x_1 is said to dominate a solution x_2 ($x_1 \prec x_2$), if and only if $f_i(x_1) \leq f_i(x_2)$, for all $i \in \{1, \ldots, k\}$ and $f_j(x_1) < f_j(x_2)$ for at least one $j \in \{1, \ldots, k\}$. A feasible solution $x^* \in X$ (and the corresponding outcome $f(x^*)$) is called Pareto optimal if there is no other solution that dominates it. The set of Pareto optimal outcomes, denoted by X^*, is often called the Pareto front. These solutions are incomparable to each other since none of these solutions can be said to be better than others, representing different trade-offs between alternatives for the given objectives [59].

To visualize the notions associated with a MOO problem, Figure 17 shows in the example several solution points in the objective space.

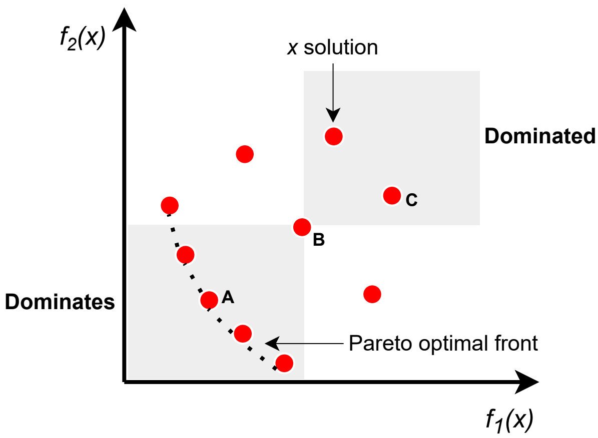

Figure 17: Example of minimization problem with two objectives.

Analyzing Figure 17, there are two major sets of points, namely the set of non-dominated solutions and the set of dominated solutions. For instance, point C is dominated by point B, $f(B) \prec f(C)$, and in turn, point B is dominated by point A, $f(A) \prec f(B)$. The Pareto optimal front indicates the non-dominated solutions that present the best trade-off solutions between the objectives. Thus, the Pareto optimal set comprises the optimal set of solutions for the given optimization problem, where compared with other solutions, these solutions converge better. Moreover, all solutions in the Pareto optimal front are non-dominated by each other and therefore the non-dominated solutions need to be chosen and maintained carefully [122].

To solve MOO problems, especially two types of methods can be used, The first, more classic and that in a traditional way are also known as scalarization methods, consists of aggregating all the objective functions into a single objection function function (e.g., weighted sum method, Tchebycheff scalarization method) [130, 143]. However, the scalarization methods may involve several parameters that can be difficult to define the appropriate weights in order to obtain different approximations to the Pareto optimal solutions. The second broad strategy, based on evolutionary algorithms, involves approximating the complete Pareto optimal set or selecting a representative subset [114]. These algorithms can be metaheuristics that mimic the process of evolution of a population of individuals over generations. These algorithms applied to MOO problems have several advantages, namely, they work with a population of candidate solutions, which makes it possible to approximate the entire Pareto optimal set in a single run. In addition, its performance is strongly related to the efficacy of its selection mechanism that guides the search in the objective space, balancing convergence and diversity and also the variation mechanism that is responsible for the generation of offspring.

In this sense, one of the best-known evolutionary methods is the elitist non-dominated genetic sorting algorithm, NSGA-II, that was adopted in this work [61]. This multi-objective evolutionary algorithm mimics how species evolve naturally and is based on groups of individuals formed at random. Each individual is a feasible solution to a multi-objective optimization problem. Crowding measures and the Pareto rank are employed in NSGA-II to score each member of the current population. The algorithm follows the general outline of a GA with a modified mating and survival selection. In NSGA-II, first, individuals are selected frontwise. Doing that will create a situation where a front needs to be split because not all individuals can survive. In this splitting front, solutions are selected based on crowding distance. However, the extreme points are desired to be kept every generation and, therefore, get assigned a crowding distance of infinity. Furthermore, to increase some selection pressure, NSGA-II uses a binary tournament mating selection. Each individual is first compared by rank and then crowding distance. If two solutions are chosen, the solution with the lowest non-domination rank will be selected. Otherwise, the one with the largest crowding distance is chosen when the two solutions have equal ranks. After that, genetic operators like recombination and mutation produce an offspring population. The two populations are combined to establish a new population that is structured along various non-dominated fronts. All members of the first non-dominated frontier are chosen as the new population if their size is smaller than the existing population. From the subsequent non-dominant fronts, the remaining population members are chosen in rank order. The practice of using NSGA-II for solving MOO problems is increasing, especially in the last years [201].

At the end of the MOO approach and in order to facilitate the decision-making process, an *a posteriori* method in which the search for an approximation to the Pareto optimal set can be performed before the process of choosing the solution. Thus, the decision-maker can select the most suitable solution from this set according to their preferences.

3.3 Distributed Artificial Intelligence

In recent years, there has been an intense demand for intelligent, re-configurable, and responsive systems to meet the pressures imposed by customers who demand more customized, low-price, and high-quality products [97].

Emergent ICT technologies, such as distributed AI, a computing paradigm that bypasses the need to move vast amounts of data and provides the ability to analyze data at the source. Gartner [141], a global provider of business insights, estimates that by 2025, 75% of data will be created and processed outside the traditional data.

Thus, AI can support the development of intelligent and distributed solutions by providing data analysis solutions, such as distributed problem-solving approaches, like MAS [128, 203, 207]. In contrast with traditional centralized and hierarchical approaches that split the problem into hierarchically dependent functions, MAS is characterized by decentralization and parallel execution of activities based on autonomous entities.

3.3.1 Agent and Multi-agent System

MAS is composed of a society of intelligent, autonomous and cooperative entities, called *agents*, that can represent the physical or logical objects of a system. The agents interact and coordinate their activities based on the local knowledge and skills, to achieve their objectives and perform a set of tasks [207, 203]. Furthermore, they offer the possibility to design large-scale, intelligent and self-organized systems, decentralizing the control by distributed entities. Therefore, the concept of *agent* is something that acts, capable of producing a certain effect. According to Russell and Norvig [176], the notion of agent is given by:

> *"An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators."*

Regardless of its definition, an agent is characterized by its capabilities to act and flexibly adapt, effectively responding to changes in the environment by sensing the environmental changes in states. In addition, the agent also has autonomy and its pro-activity allows it to take the initiative to achieve its own goals [208].

These software agents have the following properties as their main features: autonomy (operate without the direct intervention of humans), social ability (languages and communication protocols), reactivity (observe their environment and respond) and pro-activity (ability to display goal-driven behaviours) [207]. In addition, agents interact with other components, e.g., to provide services share information and exchange knowledge, in order to self-adapt or perform distributed and collaborative problem-solving and decision-making in open and dynamic environments [207, 124]. Besides their core functionality (sensing, reasoning and acting), the agents also work as a vessel for different kinds of processing and control algorithms, such as those based on AI [176]. In this sense, *agents* can be distributed along the Cloud, mobile or digital interfaces, encapsulating the system functionalities and data analysis capabilities, interacting and collaborating with each other to achieve the system's goals [128].

Figure 18 illustrates an example of a conceptual MAS in terms of the agents, their organization and their interaction with other elements. The agents differ from the conventional approaches due to their inherent capabilities to adapt to condition changes based on their internal state and their perception of the environment, in an autonomous manner, i.e., without external intervention [128, 207].

A MAS is constituted by a network of agents, which can be distributed across different systems (e.g., containers). Agents can have organizational relationships (dashed orange line in Figure 18), typically interact with each other and can have areas of influence represented in the physical environment. As opposed to centralized and rigid structures that are unable to address flexibility, robustness, and on-the-fly reconfigurability, in this approach (MAS), system behavior emerges from the interaction among the agents, where decisions are made in a decentralized manner [128, 203]. Consequently, MAS is a suitable method for designing distributed and autonomous smart

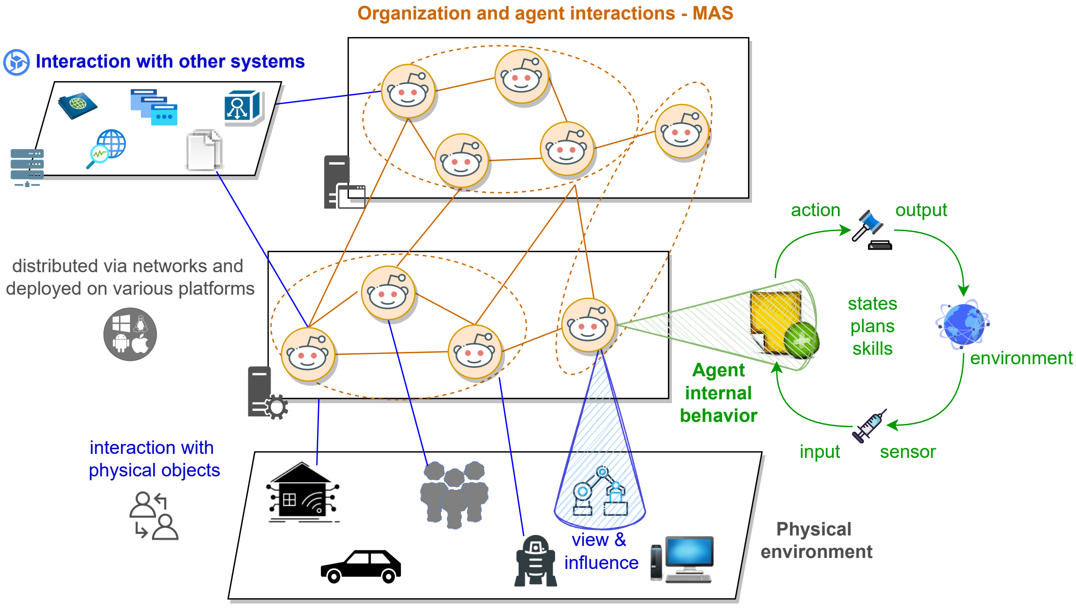

Figure 18: Example of a conceptual MAS and its key elements [84].

components with fast solutions, embedded data analysis, and collaborative capabilities [128]. For instance, MAS can handle the autonomy and mechanisms required between distributed cyber-physical components (e.g., incorporating data analytics and decentralizing decision-making), as well as the dynamic system adaptation (e.g., based on collaboration, communication and negotiation protocols and self-organization strategies that can also support the vertical and horizontal interaction and system interoperability).

In fact, in the literature there are several works that report the use of the MAS approach in the industry 4.0 domain, including control automation, production planning, supply chain and logistics [71, 126, 125]. On the other hand, MAS were and still are widely used in services, such as real-time resource allocation, scheduling and optimization [185]. Furthermore, it is necessary to highlight the design and application of MAS for HHC routing and scheduling solutions [139, 178, 149].

3.3.2 Typologies and Technologies

3.3.2.1 Agent Typologies and Communication Protocols

A single agent in some cases can be sufficient to control, monitor or carry out the execution of tasks. However, some tasks need to be performed by more than one agent due to size and/or complexity, thus giving rise to the concept of MAS. MAS comprises a society of agents that interact to achieve their goals. Each agent, despite the need to meet its own goals, can act on behalf of different users or perform tasks to meet the purposes of an application. Considering the previous information, it is important to mention that there are different types of agents, where reactive agents, belief-desire-intention (BDI) agents, and cognitive agents, among others, stand out [124]. For example, a reactive agent acts only in response to external stimuli (immediate environment events) and generally uses simple rules to map sensory inputs into motor actions. In contrast, a BDI agent has beliefs, desires and intentions and acts according to these mental states to plan and execute actions based on goals and objectives. On the other hand, cognitive agents have more advanced reasoning abilities than reactive agents, can learn from past experiences, and can use deductive and inductive reasoning to draw conclusions.

However, different typologies of agents can be used in MAS and this can affect communication and cooperation between them. To succeed in their interactions, they require cooperation, coordination and negotiation skills [176]:

- Cooperation - the ability to work together to achieve common goals, when a single agent cannot achieve them alone;
- Coordination - the ability to manage the inter-dependencies between activities, for example, using non-shareable resources or performing a sequence of tasks;
- Negotiation - communication mechanisms, such as Contract-Net Protocol (CNP) (pioneering protocol concept that employs bidding concepts [186]), with the ability to make agreements on issues of common interest, for example, through an offer and counter-offer from the parties involved.

This interaction can be supported by the use of an Agent Communication Language (ACL) and a set of interaction protocols. There are two major ACL, namely the Knowledge Query and Manipulation Language (KQML) [88] and the Foundation for Intelligent Physical Agents - Agent Communication Language (FIPA-ACL) [118, 32]. Both languages use speech act theory to provide semantics to messages through a set of speech acts, called *performatives* [115].

The *performatives* are used by agents to represent or interpret their requests and intentions, thus, when a message is received, an agent is able to understand the sender intentions and decide what to do. For example, some *performatives* specified by FIPA-ACL (interaction protocol used in the thesis) are:

- *Inform* - used to indicate that the agent is communicating information or a fact;
- *Request* - used to indicate that the agent is requesting a service or information;
- *Agree* - indicates that the agent agrees to a request from another agent;
- *Not Understood* - used to indicate that the agent did not understand the received message.

While the ACL specifies the messages of agents, the interaction protocols specify the sequence of messages exchanged between two or more agents in a given scenario, both for an information or service request, as well as for negotiation and cooperation.

In practical terms, an interaction protocol for any scenario, through the Foundation of Intelligent Physical Agents (FIPA) specifications and based on FIPA-ACL messages, allows an initiator agent to make a specific request to a participating agent. In turn, the participant can decline or can agree and notify the initiator if necessary. In case of agreement, the participant will be able to issue, for example, a failure or inform the result. According to this type of interaction protocol, it can be scalable in terms of its specification (source - FIPA-ACL specifications[1]).

Agents and more specifically MAS, have already proven their capabilities across a multidisciplinary application namely, manufacturing control [127, 180], production planning [48], logistics [204], health [178] and many others [71].

[1] http://www.fipa.org/repository/aclspecs.html

3.3.2.2 Frameworks and Agent Platforms

Some software platforms and frameworks, are well known, such as JADE [33], Repast [154], NetLogo [193], Jason [41], Jadex [165], among others more recent ones, such the case of the Python Agent DEvelopment framework (PADE) [140]. The purpose of these tools is to simplify the development of agents so that developers do not have to worry about the basic infrastructure for the execution of agents, such as the infrastructure of communication between them and other features inherent to the MAS approach. Generally, the agent platforms offer a set of built-in features for the development and execution of agents. In order to ensure interoperability between heterogeneous agents developed on different platforms, many standards and specifications for the agent technology have been developed.

In this PhD thesis, the JAVA Agent DEvelopment Framework (JADE) development tool was used as a technology for the development of MAS. JADE is an open source platform for peer-to-peer agent based applications for MAS. Moreover, JADE is a software framework fully implemented in the Java language, consisting of an API with several packages. It simplifies the implementation of MAS through a middle-ware that complies with the FIPA[2] specifications and through a set of graphical tools that support the debugging and deployment phases [168]. FIPA makes the results of its activities available to all interested parties and intends to contribute its results to the appropriate formal standards bodies, where appropriate.

Figure 19 presents the JADE architecture, resulting from the implementation of all the basic FIPA specifications that provide the normative framework within which FIPA agents can exist, operate and communicate.

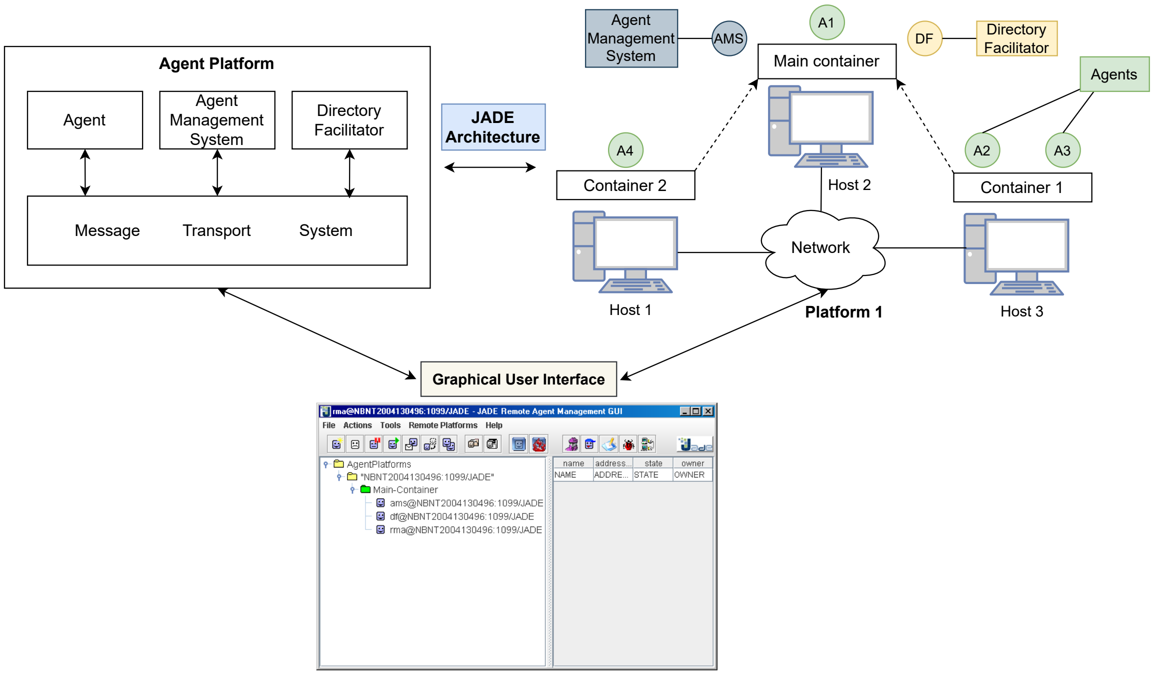

Figure 19: JADE architecture based on FIPA-compliant and main “GUI” for remote monitoring agent.

The agent platform provides a Graphical User Interface (GUI) for the remote management, monitoring and controlling of the status of agents, allowing, for example, to stop and restart agents. The GUI also allows creating

[2] http://www.fipa.org/

and starting an agent execution on a remote host, provided an agent container is already running. The GUI allows controlling other FIPA-compliant remote agent platforms.

From the JADE main functionalities, it can be seen in the infrastructure that the main container can be launched from the tools menu of the Remote Monitoring Agent (RMA), different facilitating tools, how to interact with the Directory Facilitator - DF or yellow pages (descriptions or modification of the registered agents), access the agent management system - AMS, dummy agent (inspecting message exchanges among agents), sniffer agent (track messages exchanged in the platform), introspector agent (monitor and control the life-cycle of a running agent), and also enable the message transport system - MTS.

A JADE-based system can be distributed across machines (agents execute within containers) and the configuration can be controlled via remote agent management using the GUI. The configuration can even be changed at run-time by moving agents from one machine to another, as and when required.

Besides the agent abstraction, JADE provides a simple yet powerful task execution and composition model, based on the asynchronous message passing paradigm, a yellow pages service supporting publish-subscribe discovery mechanism and many other advanced features that facilitate the development of a distributed system. In practical terms, it is possible to model an agent (*= one thread*), perform mobility and cloning procedures (Agents can migrate throughout containers), agents have behaviors (tasks, executed concurrently) and may even consider cooperative or sequential behaviors. JADE it was also designed to transparently deploy agents to different Java-oriented environments such as Android devices.

3.4 Hybrid Approaches

A hybrid approach is a combination of two or more computational techniques that are more advantageous and robust when used together than when used individually. Combining the components from various algorithms is currently the most successful and effective trend in optimization. It can help to improve data analysis, support decision-making and try to find more and better solutions.

The great motivation inherent in hybrid approaches is to acquire better-performing systems or structures that explore and associate the benefits of different pure approaches, that is, hybrid systems that supposedly benefit from synergy. The idea behind this approach is to model the problem taking into account a hybrid solution method, which can integrate solution strategies including two or more techniques in collaboration, such as exact methods, decomposition techniques CG, use of relaxations, metaheuristics and MAS [4, 183, 190].

However, developing an extremely effective hybrid method is not a simple task. The combination of popular metaheuristics like a swarming and evolutionary algorithms with techniques from other fields like AI or OR form the basis for evolving more efficient and robust solutions [199]. Blum et al., [38] highlights an important survey in this topic.

Despite the promising research that combines these types of approaches and areas, there are still some existing gaps and limitations. For example, modeling difficulties, that is, the combination of different methods can lead to greater complexity in modeling the problem, which can make it difficult to find an optimal solution. Algorithm selection is not easy, as it is important to select the correct algorithms for each part of the problem, and the wrong choice can lead to sub-optimal solutions or a loss of overall performance. Another limitation is overfitting, as there may be a tendency to overfit the model to the training data, which can lead to less general solutions or more sensitivity to variations in the data. Furthermore, the computational cost of combining different methods can lead to an increase in the time to obtain optimal solutions, which can be a problem in real-time systems. Finally, there is still a lot of dependence on data (and updated), that is, hybrid approaches depend on the quality and availability of input data, and flaws in this data can lead to incorrect or less accurate solutions. It is important to remember that these gaps and limitations (which apply for example to HHCSRP) may vary depending on the specific application and techniques used, so it is important to evaluate each case individually.

3.5 Summary

In this chapter, particular emphasis was given to the presentation of models in the optimization area and their solution methods, MAS with its intelligent structure of agents and other principles and paradigms, which in general can be proposed to address the challenges of a design and development of decision support approach to address HHC logistics.

4

Distributed Architecture for Scheduling and Routing in HHC

"The perfect kind of architecture decision is the one which never has to be made." - Robert C. Martin.

The lack of computational availability in the real-time operational management of HHC services is still present today, namely in the ongoing crisis caused by the COVID'19 pandemic. Assisting and reinforcing smart systems with decision-making support in HHC is urgently needed to free up hospitals and healthcare institutions.

The development of optimized and distributed capabilities in HHC systems can be achieved using methods and models, such as those proposed in Chapter 3, but also supported by cloud services and/or complementary tools. In this context, the proposed robust system architecture defines a general guideline to support the system during requirement analysis and design phases to determine how to distribute and balance the data analysis capabilities among the computational layers for scheduling and routing solutions.

4.1 A general guideline to design a Home Health Care Architecture

Nowadays, the decision-making process based on planning and scheduling is very important in the manufacturing domain and industries, economics, health, and service management [8]. Real environments such as HHC have a high level of uncertainty, specific requirements, several variables and objectives that are diverse and sometimes conflicting. Thus, the ability to innovate effectively and efficiently in decision-support systems is crucial, since manual solutions, or just classical methods, usually generate a centralized behavior, with deterministic and static solutions.

The proposed guideline comprises two parts. The first part, which serves as the basis of this recommendation, defines five major components to help system engineers and developers identify the key challenges related to the needs and limitations of the application scenario when designing and creating a distributed architecture. The second part defines key steps to configure a decision support system that considers 10 criteria.

The present guideline illustrated in Figure 20, aims to develop an intelligent and decentralized infrastructure, based on specific criteria, personalized workflow, smart modules, such as MAS or optimization layers, or a dashboard interface. Furthermore, the architecture must incorporate sustainable models and formulations to be properly adopted by organizations that produce operational planning with real-time flexibility, responsiveness and algorithms processing, especially in unexpected events.

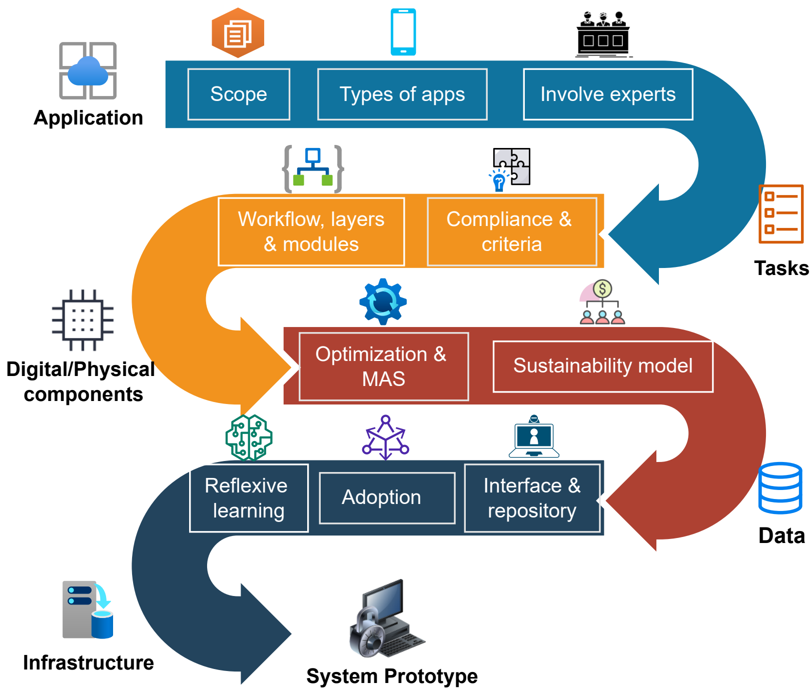

Figure 20: Guideline for major components and key steps when setting up, developing, and assessing a custom architecture.

The five major components aim to help answer the questions about how to decentralize intelligence in applications but also help to understand better why, when, where, and most importantly, what should or could be decentralized. Each aspect raises several concerns that engineers need to keep in mind when designing and developing such approaches, in order to properly address or mitigate their implications and impacts.

As shown in Figure 20, the conceptual framework considers five key factors to establish a basic structure that will help determine the needs for data analysis and the associated issues. Keep in mind that these factors represent the most typical issues considered when designing the architecture of *m-Health*[1] services.

1. *Application* domain - what are the requirements, assumptions and restrictions of the application scenario and how can they affect the solutions, data analysis and decision-making capabilities?

2. *Tasks* - what are the tasks or system functionalities, and how could they be supported or enhanced by the optimal and smart solutions?

3. *Digital/Physical Components* - what are the digital or physical components, their computing resources, and how can they be enhanced with the model data?

4. *Data* - what data are available or required and how should they be integrated, stored, analyzed, and solved? and,

5. *Infrastructures* - what are the available or required infrastructures, interfaces, or services, and how can they support achieving dynamic solutions?

[1] m-Health is a general term for the use of the digital web or mobile devices and other wireless technology in medical care.

Each of the major components of the guideline is supported by a specific question that should be answered, considering several concerns and general requirements regarding the system functionalities. Based on these questions, it is possible to organize a set of answers related to the application domain for the required infrastructure, such as healthcare (ambient assisted living hospitals, HHC operational decisions and m-Health) but is not limited to this domain and may include Transportation (vehicle navigation, routing). Regarding the domain of tasks, these can include monitoring (visualization, logging/reporting, alerts), control (process automation, cloud-in-loop navigation), supervision (decision support, task execution, organization, maintenance), planning and optimization (performance and resource management) and simulation (condition or scenario, tests, recommendations). In terms of digital/physical components, answers may include legacy equipment (digitalized), sensor and actuator (data acquisitions, sampling, response time, autonomy), mobility and software platforms (solvers, online services) and management (distributed or heterogeneous nodes). As for the domain of the data, the type will be taken into account (series, image, text, documents), integration (data collection, pre-processing, annotation), data storage (short or long term, local or remote, cost/performance, volume) and analysis (algorithms, models, complexity, uncertainty, responsiveness). Finally, the Infrastructure can rely on network aspects (technology, protocols, security, privacy, and performance), component interaction (negotiation, collaboration, hierarchy, distributed data sharing), cloud solutions (platforms and tools, data analysis services), and human interaction (visualization, user interfaces, user experience).

Furthermore, according to the guideline, the keys steps to achieve a system prototype involve the following:

- Scope - ensure the access and use of digital health innovations for routing and scheduling in HHC services (e.g., allocation, repositories). Provide policy-makers and assist decision-making with smart and optimized solutions.

- Types of apps - level of complexity, language, and customization (e.g., web and mobile app).

- Involve experts - involve experts and organizations to ensure that all aspects can be addressed, evaluated, and updated.

- Compliance & criteria - guarantee personal data protection and define criteria (e.g., goals, requirements, restrictions) to apply in all use cases and frameworks.

- Workflow, layers & modules - specific assessment phases, layers with different responsibilities and built-in modules can be defined.

- Optimization & MAS - refinements based on optimization methods and strategies, aggregated with smart, distributed, and autonomous solutions.

- Sustainability model - evaluation of cost, platform maintenance, scalability (function seamlessly across a large network), and ability to integrate different solutions and algorithms.

- Interface & repository - technical implementation and detail of the web/app (mockups) and repository in terms of language, components, interactions, transparency, security, filters and connection.

- Adoption - Identify the end-users to communicate and disseminate. Carry out training with health institutions and professionals.

- Reflexive learning - what worked, what did not, and adapt the process according to the received feedback in user usability.

The proposed guideline to design an architecture incorporates concepts of artificial and swarm intelligence, optimization methods and cloud information. The resulting architecture will assist in the automation of dynamic scheduling, based on the distribution of control functions over a swarm network of decision-making entities. This challenge will seek to combine the strengths of MAS, which allow for fast and reactive responses to uncertain conditions, with optimization methods to produce innovative optimal solutions, in an attempt to both generate robust and flexible behavior in emerging domains, such as HHC.

Note that the proposed guideline does not intend to list and discuss all possible aspects, since they vary according the application domain and scenario. Therefore, it should be considered a general guideline, where its structure allows it to be easily adapted or extended to support other scenarios and related aspects.

4.2 Conceptual Structure for Distributed Systems

Systems need to be configured and optimized in an evolutionary manner as dynamic settings become increasingly complex to satisfy the growing demand. When dealing with real-world situations or unexpected circumstances, centralized and static approaches may experience bottleneck problems and become challenging to change [8]. Consequently, each change to the specifications of systems or products may require the distributed scheduling and resource allocation of simpler services.

Thus, in the first phase of the research, the idea of designing a configurable framework focused on HHC support emerged, which would interconnect the problem requirements (routing, planning, scheduling) with digital and optimized solutions (optimal solutions, digital interface), based on a communication constantly using the internet (as represented in the Figure 21).

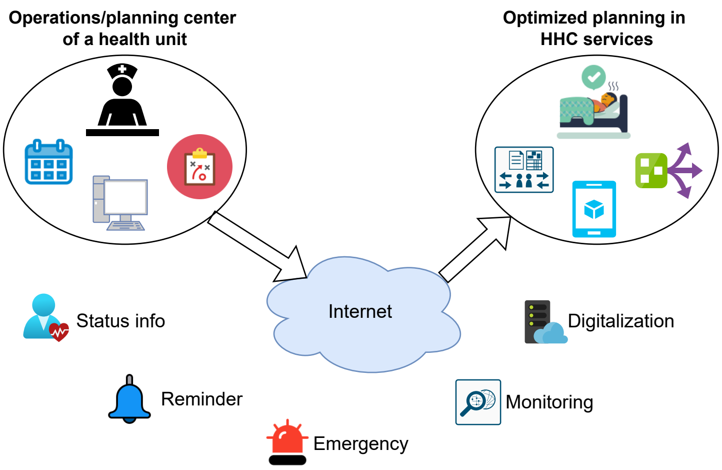

Figure 21: Initial idea to modernize, support, and optimize the Home Health Care service.

This initial design of how to solve an increasingly current problem and with emerging needs was intended to include Information and Communications Technology (ICT) concepts and technologies, allowing the use of a database, automatic reminders, support for decision-making in emergency situations, monitoring operational activity and digitalization of service information.

ICT is the infrastructure and components that enable modern computing. This infrastructure can represent many devices, networking components, applications and systems that, combined, allow people and organizations (i.e., nonprofit agencies, governments and healthcare institutions) to interact in the digital world, especially in the context of the COVID'19 pandemic [197].

4.2.1 Infrastructure and main components

ICT encompasses both the internet-enabled sphere as well as the mobile one powered by wireless networks. In addition, they can include ICT pieces such as optimization, artificial intelligence, and digital technologies.

Thus, the infrastructure was designed to support the collaboration of different components, which may be specialized or form part of the general system, such as engine components. The platform in its basic form is installed at each node (it can have different engines from external devices or platforms) while the specialized components have a distributed implementation over cloud services. Furthermore, according to Figure 22, the four levels of the infrastructure are represented.

Briefly, and presenting the block diagrams in Figure 22 from bottom to top, the external level is represented, which includes communications, integrated devices and sensor/networks. This external level supports communication over the network and interfacing with external devices. Specifically, this level is responsible for safe communication between network nodes. Furthermore, this level abstracts communication between devices, acting as a bridge for the system to interface, monitor and report.

In the next block of the infrastructure, the MAS level is represented, where an agent-based model will be taken into account as an engine platform. This level is one main component of the diagram that supports the creation, launch, reception, and execution of stationary and mobile agents and their autonomous interactions to achieve distributed solutions for fast allocations or during unexpected events. Still, in the general system, the optimization level is represented, where different optimizers (platforms, tools, among others) will be able to support decision-making in an optimal or at least more optimized way. This level will serve as an engine for the ability to optimize solutions for building and implementing routing and scheduling problems through mathematical techniques and formulations, using evolutionary algorithms, multi-objective strategies and combinatorial and/or exact approaches for different criteria and objectives.

In this sense, the approaches and algorithms used, both at the optimization level and MAS, the main engines of the infrastructure, will enable the system to provide optimized responses, smart decisions, scalability and multi-dimensionality.

Finally, the top block represents the specialized components, where different types of services are allocated, which will support the remaining levels and blocks. These services represent the application level and consist of base services that provide functionality for the other vertical services, including web service access, virtual community support, and specialized interfaces. The top services support different interactions within the system.

In summary, the main components of this ICT infrastructure are based on software, hardware, transactions, communications technology, data, internet access and cloud computing. ICT is generally accepted to guide all computer and technological components that, combined, allow people and organizations to interact in the digital world.

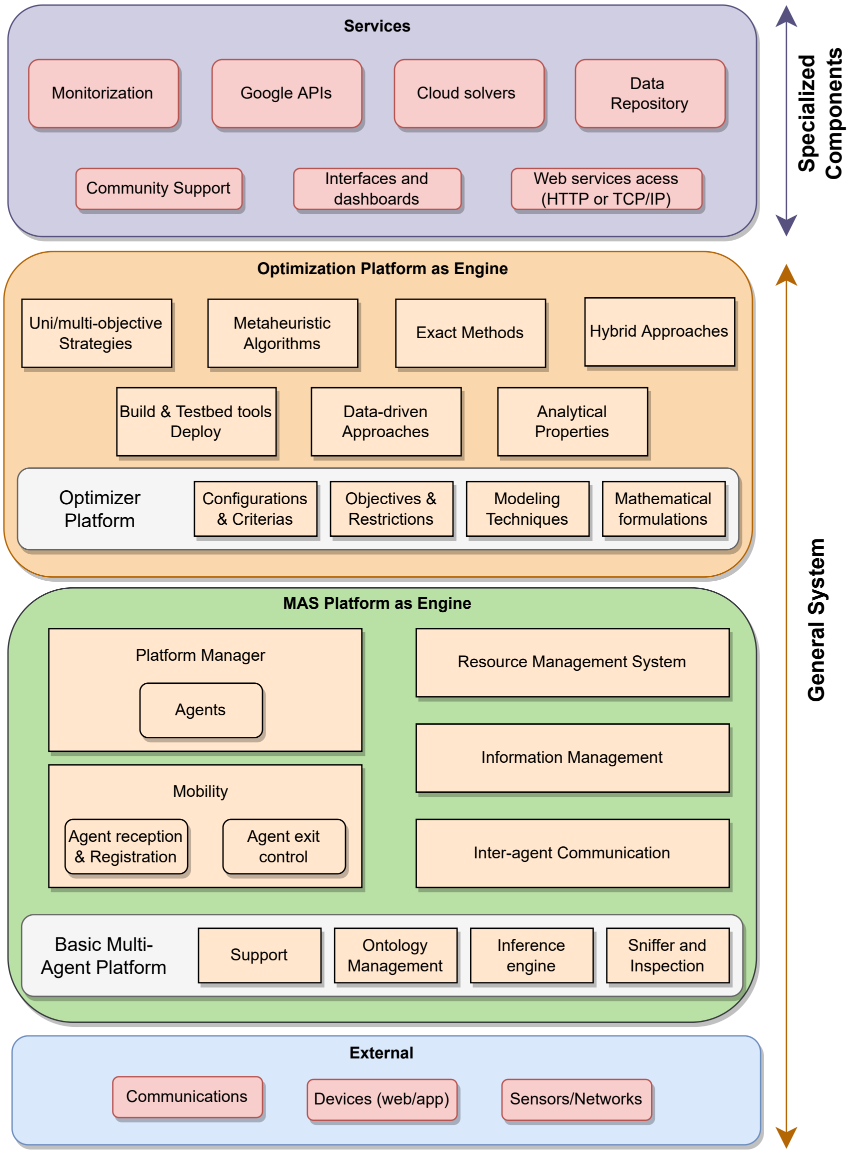

Figure 22: Infrastructure block diagram.

4.2.2 General Architecture and Modules

The designed infrastructure allows to innovate and contribute to a modernized architecture, with a digital ecosystem for distributed HHC. The main idea is to address the lack of dynamic and optimized solutions in a single system that can meet HHC rising needs [12].

Figure 23 shows a smart architecture with an adaptive scheduling approach and distributed computing. It proposes integrating a well-structured system, employing ICT concepts to specify in an interface module, inherent communication, monitoring, and HHC decision-making. By leveraging an architecture that benefits from a collaboration of an API, connected with a cloud repository, optimization node, a distributed artificial intelligence module and a dashboard interface, an approach is proposed based on a custom conceptual design that allows distributed and intelligent management to promote technological innovation in basic concepts of society for more sustainability in everyday applications in domains with emerging needs, such as HHC operational systems.

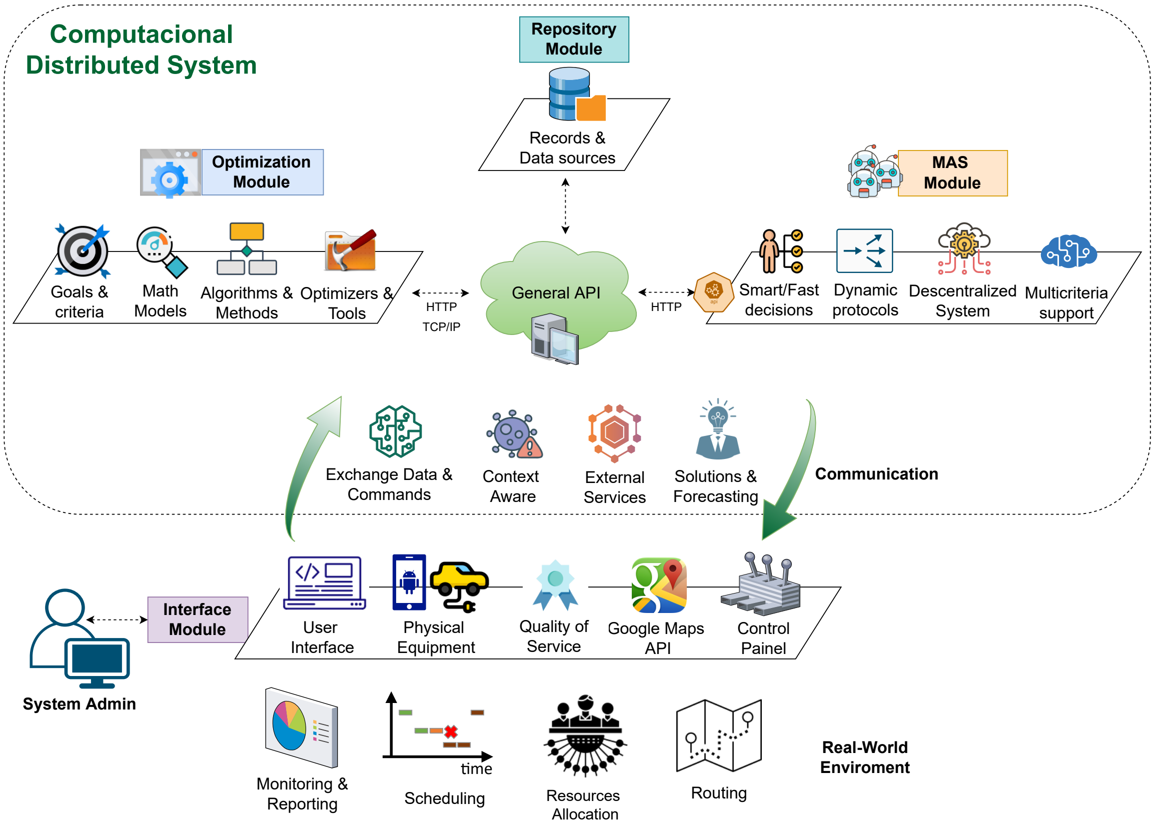

Figure 23: General system architecture and respective integral modules.

The mockup modules are designed with intelligence and optimization skills to use HHC providers' resources efficiently. In summary, the computational distributed system provides a digitalized infrastructure that can offer lower costs, scalability, and component flexibility when designed as a cloud.

In this way, it is important to mention the functionality and interoperation of each component/module. Thus, the behavior of the system is described in the diagram of Figure 24, which shows the sequence of operations that the system performs (by its various components), using Unified Modeling Language (UML). The user initiates interaction with the distributed computational system by logging in through the interface module. The general API receives the communication, manages and monitors the three modules of the system: repository, optimization and MAS.

The system may acquire, store, and retrieve the data set to manage using the general API and access to a database with medical records (health unit collaboration). The components will include a RESTful[2] server for displaying micro-services. Depending on the HHCSRP that needs to be solved, the user can choose to use only the optimization module, only the MAS module, or use both simultaneously as solution approaches.

If the user chooses to use the optimization module, the system, through the general API, will communicate with him and perform the necessary operations to provide input and solve the planning problem. On the other hand, the optimization module will be able to communicate with the service layer, collaborating in optimized (or "optimal") scheduling solutions. This module will feature advanced technologies, such as mathematical models, criteria and goals definition, use of metaheuristics (e.g., GA and PSO) or exact methods based on integer linear programming

[2] Representational state transfer (REST) is a software architectural style that describes a uniform interface between components, often across the Internet in a client-server architecture, based on HTTP methods such as GET and POST.

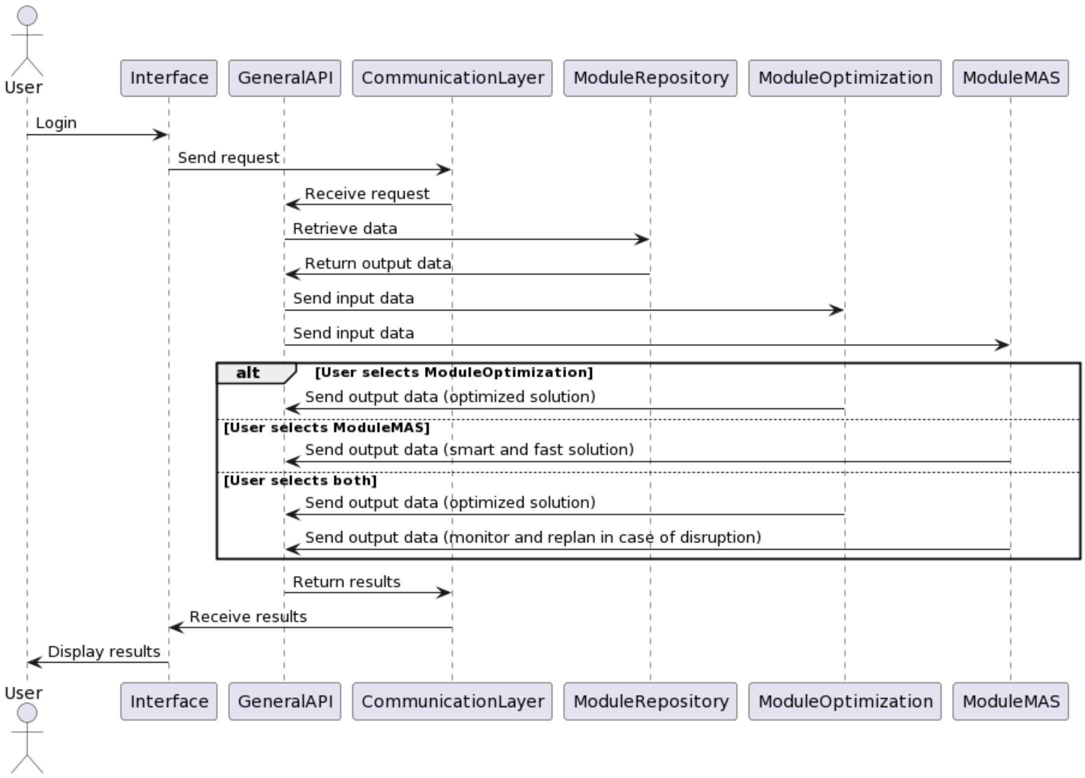

Figure 24: System behavior and sequence of operations.

(BB). In addition, multi-objective optimization approaches for conflicting goals will be available, providing better support for decision-making. Furthermore, different optimizers (e.g., MatLab) could be considered for more dedicated and customized software resources for numerical calculation and optimization. This module will be devoted to most problems and can be solved stochastically or deterministically.

If the user chooses to use the MAS module, the system, through the general API, will communicate with him and perform the necessary operations to solve the allocation problem. The MAS module will be fully equipped with a smart platform (e.g., JADE) that will communicate with the service layer to support automated planning using distributed AI. Agent interactions and information sharing make decentralized problem-solving and distributed scheduling possible, allowing the system to efficiently come up with new solutions, especially for smart/fast response in surgical emergencies. The idea is to support the interaction and message exchange between agents and their environment to ensure the best collaboration and negotiation to reach the best solutions. The specification of the negotiation protocol is presented according to the Agent Unified Modeling Language (AUML) formalism, which extends the UML for intuitive graphical representation and is preceded by a general design for the entity relationship, set of properties, and general attributes of the custom CNP, as illustrated in Figure 25.

In general, the interaction begins when a patient agent needs to schedule a service (treatment or specific need), where he sends a call for proposals (*cfp*) to this list of available health professional agents. This agents can send (or not) their proposals to the agent who requested the tasks and if yes they need to calculate the "price" to execute the treatment and send a (*propose*) to the patient agent. On the other hand, the patient agent receives different proposals and determines the best that maximizes/minimizes its priority/utility function. The MAS offers a rapid evolution framework that encourages cooperative action, multi-criteria strategies using dynamic protocols among autonomous agents, and dynamically adapts behavior using multi-criteria support.

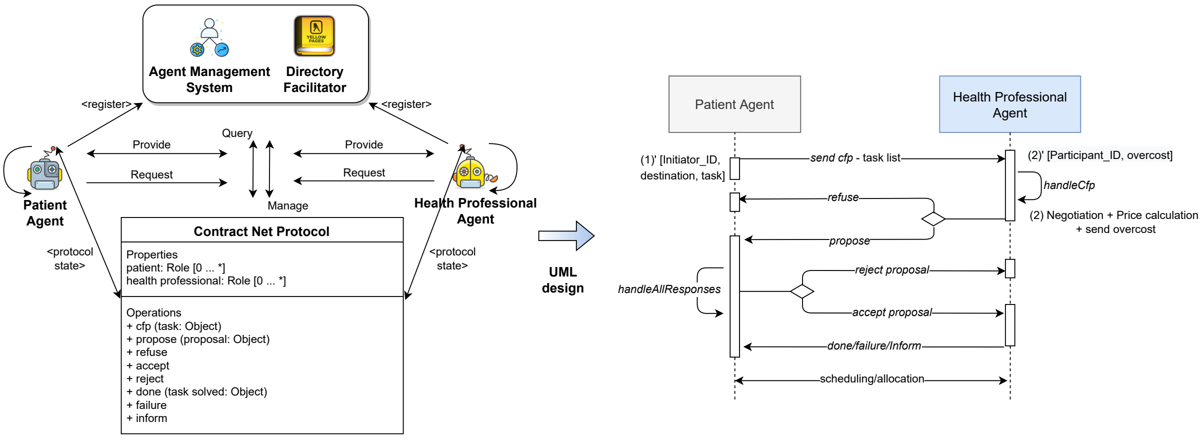

Figure 25: Design of the negotiation protocol and interaction of agents based on the CNP sequence diagram.

Finally, the user has the possibility of using both modules together, and so the system will communicate with both modules and perform the necessary operations to solve the planning and scheduling problem simultaneously in a hybrid way. The system uses a communication layer to exchange data between the different modules of the system and the general API in the end returns everything to the interface module. Regarding the communication layer, it will be responsible for connecting the interface module and the distributed computational support. This will include data and commands exchange (formatting inputs and command outputs, data filtering), context awareness (sensitive capture of data from an environment for decision making), external services (connect cloud computing, remote working and technologies, such as Google services, Platforms-as-a-Service) and finally, solutions and forecasting (providing smart and optimized solutions, and flexible, scalable and customizable analytics). The organization (admin) linked to the whole system will be responsible for any personal data manipulation (e.g., patient), so the system will not have any privacy problems.

The interface module gives users access to the platforms through an intuitive interface, allowing for real-time monitoring of the solution state or physical equipment (e.g., phone). As a setup engine, Google Maps API will be used (maps, routes, and locations). The quality of the service will be measured in qualitative and quantitative terms and everything will be managed through the control panel in the interface.

The system increases adaptability, which is crucial to digitalizing the planning process, by proposing the interconnection of all these modules and taking into account the current gaps, which focus on centralizing the solution or do not take into account dynamic environments in the real-world environment, such as HHC management.

In summary, the proposed disruptive infrastructure will support decision-making for the practical application of HHC while fostering operational competitiveness and strategic planning to ensure efficiency in order to achieve better route combinations, better resource allocation, workload balancing, scheduling optimization and proper monitoring and reporting of the service.

4.2.3 System Interaction and Strategies

The operational management of resource allocation, scheduling, and routing configurations is the basis of most HHC information systems. Due to the complexity of their modeling, these health services are typically complex manual processes.

The proposed architecture aims to contribute to better management of visits to HHC, namely in the automated timetable allocations, circuits and routes to households in order to minimize resource usage and time, but also in terms of service monitoring and resource allocation. Due to the current need for digitalization, the product also intends to standardize and digitalize the strategic and operational management in the service to users allocated in a given Health Unit and/or IPSS, who have similar situations, scenarios and problems. The current needs of this type of organization require more and better decision-making support to ensure optimized routes, intelligent scheduling of resources, and greater efficiency in the home visit service with real-time operation.

The interactions for the proposed system architecture can be seen in Figure 26.

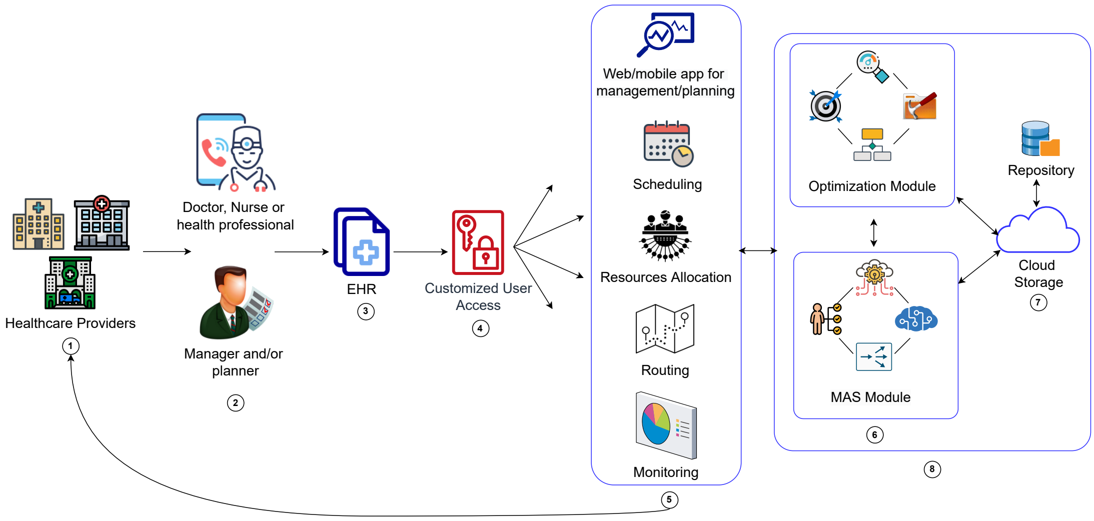

Figure 26: Representation of the interactions between the system architecture, users and service layers.

The different players in the system and integrated modules present an expected sequence of proper functioning, interactions and access to data and information, which will culminate in the creation, management, and monitoring of a real environment for HHC through an app with intelligent resources:

1. Different home health care providers (e.g., hospitals, health units or IPSS);

2. System that will allow the connection, access and management of data by the responsible health professional and/or health service manager;

3. Possible integration and access according to the existing electronic health record - EHR (e.g., SClinico).

4. Definition of custom roles or permissions for system users. System access specifications will be given depending on role, level and/or experience, for home service access, limiting the most sensitive information regarding account functions;

5. A control dashboard, based on a web and/or mobile application to make the system/information portable and digitalized, monitoring operational planning, allowing interaction with the user and vice versa. The process is repeated whenever necessary, going back to point 1.

6. Modules dedicated to mathematical models, efficient algorithms and intelligent decision-making support, for resource planning with route optimization and scheduling in HHC.

7. Integrated data repository (if possible in cloud storage), for quick access to internal data from healthcare professionals and/or data with other sources (e.g., Health Center or IPSS).

8. Informative architecture of the distributed computational system, where the data will be analyzed and processed, providing answers and assistance to its users.

Regarding points 5, 6, 7 and 8, the admin (user) will be able to manage and plan the system, carry out information updates, and monitor the interactions between modules. Figure 27 presents a flow chart that identifies the possible decision-making process of the architecture designed for the system. The user will be a critical member of the system.

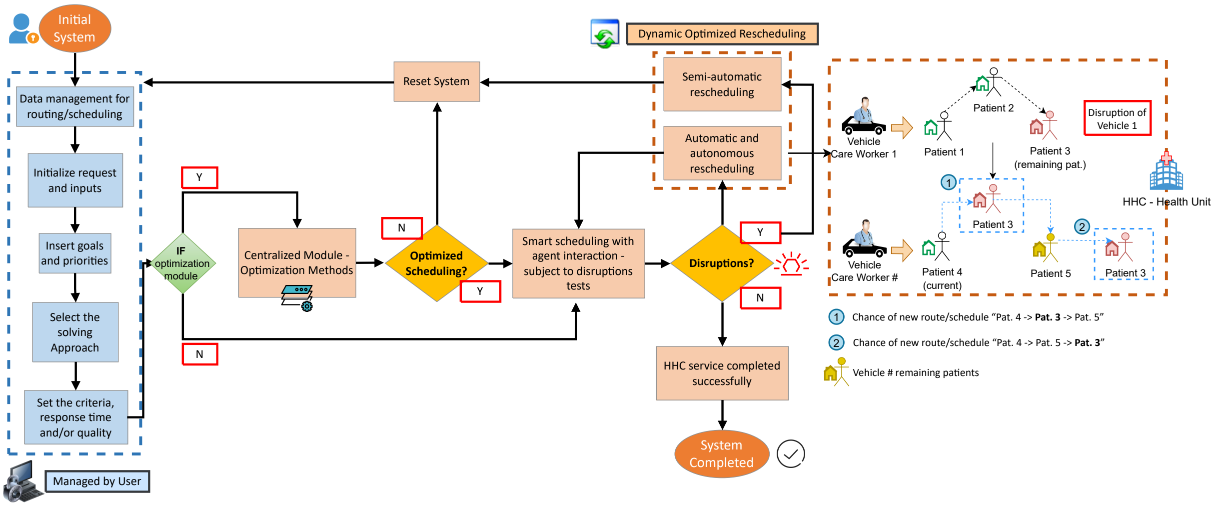

Figure 27: Flow chart of the system and to support decision-making. Adapted from [5].

After accessing and managing data in the repository, the user will have the opportunity to make requests for routes and scheduling applied to the problem under study. In turn, the user will have the option of choosing which solving approach he prefers (between integrated modules and/or external services) taking into account his constraints. By default, the optimization module is started if nothing is chosen and the MAS module will monitor the agents involved in case unexpected events arise. In the event of a disruption, the scheduling can be adjusted autonomously and automatically using agent behavior, interaction and negotiation procedures. In case of disruption, the agents model is activated, which changes from the static and passive approach (optimization module) to the dynamic and autonomous approach (MAS module). Two types of agents are considered (vehicle/care worker and patient), each with its responsibilities and behaviors. The passive behavior performance criterion analyzes the optimized planning provided by the offline module (e.g., metaheuristics coded in MatLab). If there are unexpected events, autonomous behavior is activated, where agents take control of the previously planned route and dynamically adapt the schedule through interactions between agents, seeking to minimize delay activities and interruption times.

Agent interaction has been modified to activate as soon as there are system failures. When, for example, a vehicle becomes unavailable (e.g., breakdown) and there is an ongoing schedule in hand, it is necessary to understand what to do with the remaining patients on the route that, from that point on, are no longer visited by the previously allocated care worker. In a reactive way, the care workers are still available to interact with each other (agent model) and opportunely negotiate their immediate capacity and whether or not to assume the left patients.

A communication protocol is started between agents trying to find the best solution. A set of proposals is taken into account, based on the requirements of the patients left and the current schedule in execution of each one of the care workers/vehicles. Thus, decision factors were coded, which allow the different available care workers to test the inclusion of the patients left in their current schedule, trying to fit the remaining tasks/visits at intervals (e.g., trying to fit the remaining patients in the range with the shortest distance or time). The best solution will look for global scheduling to be as optimized as possible, trying to ensure that delay does not complicate the HHC service or that some patient does not receive the proper treatment.

Thus, the combination of these interactions and strategies can guarantee task effort distribution and better solutions/planning in the management of HHC real-world.

4.3 Summary

HHC needs technological innovation due to its high complexity, constraints, and requirements. Management of the HHC system requires innovation because it is currently done manually using traditional methods (Excel), typically centralized and static. The mapping of real HHC problems allows for developing an application infrastructure of a distributed optimized and intelligent system that considers operational planning requirements, promoting a digital and sustainable ecosystem (*mHealth*). This section aims to establish a distributed and flexible architecture for routing and scheduling in HHC. It considers MAS technology to guarantee dynamic and fast responses, combined with optimization algorithms that allow optimal solutions. The information digitalization for real-time monitoring will be managed collaboratively by applying diverse tools and techniques, ensuring portability, robustness and responsiveness in a domain with emerging needs. All modules considered together could be a potentially promising approach to closing gaps in both centrally and separately used strategies.

5

Implementation and Experimental Evaluation

"All life is an experiment. The more experiments you make the better." - Ralph Waldo Emerson.

Taking into account the different strategies and theoretical techniques presented in Chapter 3, a conceptual framework with a general architecture was designed in Chapter 4. The presented architecture includes the integration modules of the various coded components to evaluate and determine the most suitable computing layer for the implementation of a given data analysis task. To support the requirements and features of the architecture, this chapter presents the implementation and experimental validation of specific models and methods, where optimization and/or intelligent agents are considered as the key enabling approaches dedicated to HHCSRP. The main idea is to present a high-level (cleaned up) description of application experiments, in different practical or theoretical implementations, considering their use in solving the research problem.

To overcome the organization's difficulties in terms of poor planning of the home service, it was necessary to codify the entire operational process of computer-assisted visits. The system integrated the number of vehicles available, the health professionals involved, the patients who request home care and, implicitly, the treatments necessary for patients and provided by nurses (or care workers), as well as the time and distance to which the various scheduling routes are subject. Furthermore, it was essential to consider some properties and general assumptions of the problems, namely geographic area, resource dimension and different instances. Different sets of mathematical models were included, from sets that contained all locations (indexed), to sets that reported on available vehicles. Furthermore, it was known in advance that all visits began and ended in the depot, the patient profiles, the maximum and minimum times and distances defined on average for the visits, and even that only one healthcare professional was assigned to each vehicle.

Based on that, the following sections describe the implementation of different experiments (some with real applications) that demonstrate some features of the components of the main core modules of the architecture. In addition to that, the objective of this scenarios are to support the evaluation and validation of the proposed general guideline, considering preliminary case studies that contain different particularities and context information that can be included (e.g., development software, test environment, procedure, limitations, assumptions, and range of validity, among other features). Quantitative and qualitative indicators will also be identified that specify the procedures for their measurement and evaluation, in order to access the performance of the developed strategies.

In most experiments and case studies, a general and experimental dataset related to data from the Health Unit of Santa Maria, in Bragança, Portugal, was used. The partnership established with the health unit of Santa Maria, at the beginning of this work, allowed the collection of data that included several flaws in the organization of the HHCSRP service. These services are provided by the National Health System, meaning that health professionals (typically nurses or health technicians) need to go to the patients' homes to perform all the requested treatments (using transportation for this purpose). However, scheduling/planning in this health unit is carried out manually (without computational support), generating complex procedures, which are generally not prepared for unforeseen events (e.g., disruptions, delays in visits, among others). Given the characteristics of the problem under study, it is interesting to characterize the data provided by the Health Unit, in particular, the important aspects for solving the problem of scheduling and routes. The collected dataset and its characterization are briefly identified in Table 5.

Table 5: Characterization of the Health Unit dataset.

Dataset	**Health Unit of Santa Maria**					
	Region	Nurses	Patients	Locations	Vehicles	Treatments
	Bragança	12	40	40	5	5

The data reveal that, as part of the care workers team, 12 nurses conduct home visits to 31 patients (data for one week only), in 31 different locations (in the Bragança municipality region, in an area of about 1000 km^2) in order to provide different types of treatments. Regarding the different locations for visits, each one has been abbreviated to protect the real data of the patients. The service nurses have different skills, that is, there may be some nurses who are able to perform all treatments, and others only one specific one. The services provided to patients mainly involve 5 different types of care: curative visit (e.g., ulcers), surveillance (e.g., vital signs monitoring), rehabilitation, cleaning and hygiene, and social support (e.g., bereavement and/or risk factors). For each type of service, the treatments may involve different average duration times, which may vary depending on the needs of patients. To carry out home visits, nurses have 5 vehicles designated for this purpose, however, at certain times of the year when the requests for visits are more regular and with greater intensity, the nurses can use their own vehicle as a means of transportation. Some data cannot be discussed in more detail due to the existence of confidential data protection. Furthermore, it is important to mention that during most experiments, different subsets of this dataset were used in order to evaluate different methods, criteria and/or scenarios.

5.1 Exact Methods

In this section, some of the exact optimal designs of experiments will be presented and discussed, via MILP and/or using a CG method. Each has its challenges, but in the end, the advantages (or disadvantages) of these approaches will be discussed.

5.1.1 Periodic VRP based on MILP

In the initial phase of the research, some experiments were carried out taking into account a Periodic Vehicle Routing Problem (PVRP) in a health unit, in particular with the Health Unit of Santa Maria in Bragança. However, this particular health or social support service involves resource management decisions, where its management and planning are usually solved manually and without computational support, which makes the complex procedures of scheduling and routing even more pronounced (NP-hard[1]).

[1] A Problem X is NP-Hard if there is an NP-Complete problem Y, such that Y is reducible to X in polynomial time.

Thus, a PVRP implementation was carried out to determine the routes for a planning horizon of multiple periods with patients demanding multiple visits (characteristic in the periodicity of visits). The objective of the periodic approach was to respect the regularities imposed by the patients, ensuring that everyone received the necessary care [22]. In this way, a MILP model was coded, which had different sets of parameters, variables and constraints as input, similar to the generalized notation presented in Chapter 3. However, there was the inclusion of a design of periodic routes for different days, considering a time horizon with different visit patterns, i.e. the patterns relate to the frequency of visits desired by patients and take into account the characteristics of the routes. To allow periodic visits, a set $L = \{1, \dots, \mathrm{l}\}$ was added, representing the l number of periodic visits required by patients (e.g., in a week a patient needs three visits with a day of rest between each visit). This will allow for the definition of multiple periods of visits for daily, weekly or monthly planning. Furthermore, in this adapted version of the generalized model, PVRP also has the following additional parameters:

- pt_i is the set of visit patterns of patient i, that means the regularity of the schedule;

In addition, other variables were considered and added to the general model:

- x_{ij}^{kl} - Binary variable that equals 1 if vehicle k travels between nodes i and j on day l; and zero otherwise;
- r_i^s - Binary variable that equals 1 if patient i is visited according to the s pattern belonging to pt_i; and zero otherwise;
- u_i^{kl} - Decision variable used to eliminate subtours involving the place in the visit sequence of vehicle k on the day l for the location i;
- a_i^{sl} - Variable to represent the s pattern that includes the patient i on day l.

In this sense, the MILP is given by:

$$\min \sum_{i \in N} \sum_{j \in N} c_{ij} \left(\sum_{k \in K} \sum_{l \in L} x_{ij}^{kl} \right) \tag{5.1}$$

subject to:

$$\sum_{j \in N} x_{ji}^{kl} - \sum_{j \in N} x_{ij}^{kl} = 0, \qquad \forall i \in N; \forall k \in K; \forall l \in L; i \neq j \tag{5.2}$$

$$\sum_{j \in N} x_{0j}^{kl} \leq 1, \qquad \forall k \in K; \forall l \in L \tag{5.3}$$

$$u_j^{kl} \geq u_i^{kl} - M(1 - x_{ij}^{kl}) + 1, \qquad \forall i, j \in N; \forall k \in K; \forall l \in L; i \neq j \tag{5.4}$$

$$\sum_{s \in pt_i} r_i^s = 1, \qquad \forall i \in N \tag{5.5}$$

$$\sum_{j \in N} \sum_{k \in K} x_{ij}^{kl} - \sum_{s \in pt_i} a_i^{sl} r_i^s = 0, \qquad \forall i \in N; \forall l \in L; i \neq j \tag{5.6}$$

$$x_{ij}^{kl} \in \{0,1\}, \qquad \forall i,j \in N; \forall k \in K; \forall l \in L \tag{5.7}$$

$$r_i^s \in \{0,1\}, \qquad \forall i \in N; \forall s \in pt_i \tag{5.8}$$

The main objective, represented by equation (5.1), is to minimize the cost of visiting patients, in terms of distance for each vehicle on service days. Equations (5.2) ensure that a vehicle that enters a location j must also leave from it, ensuring the continuity of the route. Equations (5.3) ensure that there is no vehicle overflow. The sub-circuit elimination are expressed by constraints (5.4). Equation (5.5) guarantees that every patient will be assigned to one of the admissible visit patterns (time period). Furthermore, Equations (5.6) guarantee that all patients will be visited precisely on the days of the pattern schedule (patient preference). Finally, the equations (5.7) and (5.8) specify the definition domain of the decision variables.

The real data took into account the experimental dataset, considering in this case 5 vehicles, 15 patients (15 locations) and a time horizon of 5 days, $T = 5$ (service week). Furthermore, from the data provided, it was possible to identify that between two or more visits an interval of one day is required, so a set of patterns was generated, that is, for 1, 2 or 3 visits per week. For example, for the time horizon considered, the patterns refer to the frequency of visits required by each patient, that is, for patients who need 3 visits per week, the visit pattern s can only exist no $1-3-5$ days.

The IBM ILOG CPLEX was used to implement the model presented above, using an exact method, namely the BB. The results were obtained using an Asus laptop with an Intel(R) Core i7 CPU 2.2GHz with 6.0 GB of RAM.

The optimal solution was reached after 11 hours computational time, with a target value of 473 kilometers, representing the total distance required to carry out the trips, treatments and return to the starting point. This solution indicates the minimum distance to be traveled (cost) for the available vehicles to make the home visits routes, according to the defined time horizon and periodicity (regularity) needed by the patients (as shown in the scheduling and set of routes in the Figure 28). More details can be found in [18].

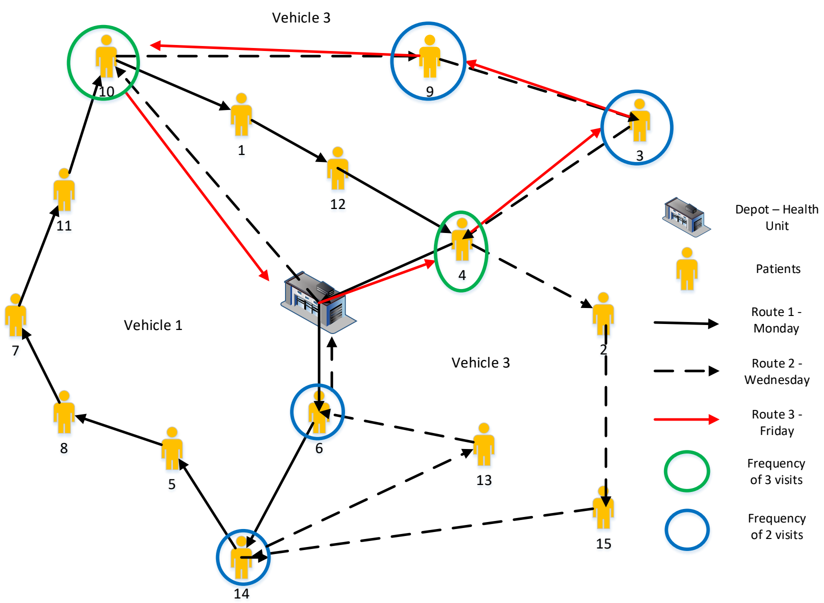

Figure 28: Representation of the periodic VRP solution.

Some patients require a higher frequency of visits. However, those belonging to more than one route and day of visit can be checked. With the approach presented, it is possible to conclude that all patients are served and that all routes meet the time period between successive visits, resulting in admissible patterns. Furthermore, the operational planning for that week did not require using the 5 vehicles available, but only 3, fulfilling and respecting the requirements and generating cost savings at the health unit.

In summary, this implementation allowed computational support to the Health Unit of Santa Maria in Bragança. However, with this approach it became clear that replicating the problem with large instances may not be feasible or attractive.

5.1.2 Column Generation Approach

Considering the challenges and limitations of the previous exact approach, which in terms of obtaining solutions required a large computational effort and turned out to be a time-consuming task, this experiment seeks to facilitate and use the benefits of a smart CG implementation for the same previous problem (PVRP). The general idea is to apply and evaluate the same experimental dataset (with the same number of instances) that was used previously.

Initially, the Dantzig-Wolfe decomposition was applied where the previous PVRP (from (5.1)-(5.8)) is decomposed into two problems, the RMP and the sub-problem to provide better bound when linear relaxation of the problem is solved [35]. The decomposition takes place with sub-problems that define the routes, i.e., the constraints (5.2) and (5.4) define the sub-problem. Since all vehicles are the same (homogeneous), the sub-problem is not associated with a specific vehicle. However, the route is associated with a day due to the demand constraints. Note that the dual variables of (5.6) are associated with days. In this sense, in addition to the parameters and variables previously considered, the following codes were described:

- A represents the set of all routes indexed by q;
- $b_{iq} = 1$ if route q includes patient i;
- $C_q = \sum_{ij \in N} c_{ij}$ represents the cost of route q;
- α_{il} is the dual variable of constraint (5.11) for each patient i and for each ℓ;
- β_{kl} is the dual variable of constraint (5.12) that lists the vehicle k for each of the days ℓ;
- h_i is a artificial variable;
- v_i binary variable that equals 1 if patient i is visited; and zero otherwise;

The RMP has decision variables $z_{k\ell q}$ that define whether route q is selected for vehicle k on day ℓ.

$$\text{Minimize } z = \sum_{q \in A} C_q \sum_{k \in K} \sum_{\ell \in L} z_{k\ell q} + M \sum_{i \in N} h_i \tag{5.9}$$

subject to:

$$\sum_{s \in pt_i} r_i^s + h_i = 1, \quad \forall i \in N \setminus \{0\} \tag{5.10}$$

$$\sum_{k \in K} \sum_{q \in A} b_{iq} z_{k\ell q} - \sum_{s \in pt_i} a_i^{sl} r_i^s = 0, \quad \forall i \in N \setminus \{0\}, \forall \ell \in L \tag{5.11}$$

$$\sum_{q \in A} z_{k\ell q} \leq 1, \quad \forall k, \forall \ell \in L \tag{5.12}$$

$$z_{k\ell q} \in \{0, 1\}, \quad \forall k, \forall \ell, \forall o \tag{5.13}$$

$$r_i^s \in \{0, 1\}, \quad \forall i, \forall s \in pt_i \tag{5.14}$$

$$h_i \geq 0, \quad \forall i \in N \tag{5.15}$$

On the other hand, the sub-problem is characterized for the vehicle k on the day ℓ, and intends to find a route i.e. the values for the x_{ij} variables, given by:

$$\text{Minimize } z = \sum_{i \in N} \sum_{j \in N} c_{ij} x_{ij} - \sum_{i \in N} \alpha_{i\ell} v_i - \beta_{k\ell} \tag{5.16}$$

subject to:

$$\sum_{j \in N} x_{ji} - \sum_{i \in N} x_{ij} = 0, \quad \forall ij \in N; i \neq j \tag{5.17}$$

$$u_j \geq u_i - M(1 - x_{ij}) + 1, \quad \forall ij \in N; i \neq j \tag{5.18}$$

$$v_i = \sum_{j \in N} x_{ij}, \quad \forall i \in N \setminus \{0\}, i \neq j \tag{5.19}$$

$$u \geq 0, \quad \forall ij \in N \tag{5.20}$$

$$x_{ij} \in \{0, 1\}, \quad \forall ij \in N \tag{5.21}$$

$$v_i \in \{0, 1\}, \quad \forall i \in N \setminus \{0\} \tag{5.22}$$

$$\tag{5.23}$$

In this work, to apply this clever mathematical approach, it is used a Gurobi Python Interface, $gurobipy$ [104]. Therefore, to facilitate the understanding of the basic procedure implemented,Figure 29 illustrates the design of the proposed approach.

The RMP is initialized with a limited number of columns. Some strategies may be applied to generate initial columns, such as heuristics, linear relaxation, old solutions (the problem may have been solved before) or random generation of initial columns (perhaps the least effective, due to the probability of generating weak solutions). As the problem under study had already been solved previously (see Section 5.1.1), it was easy and effective to generate some basic and admissible solutions, which satisfied all constraints, as a starting point for the sub-problem. The dual solution of this RMP is then given to the sub-problem to generate an attractive column, which is equivalent to produce a route with negative reduced cost. Then, the attractive column, if any, is incorporated in the RMP. This

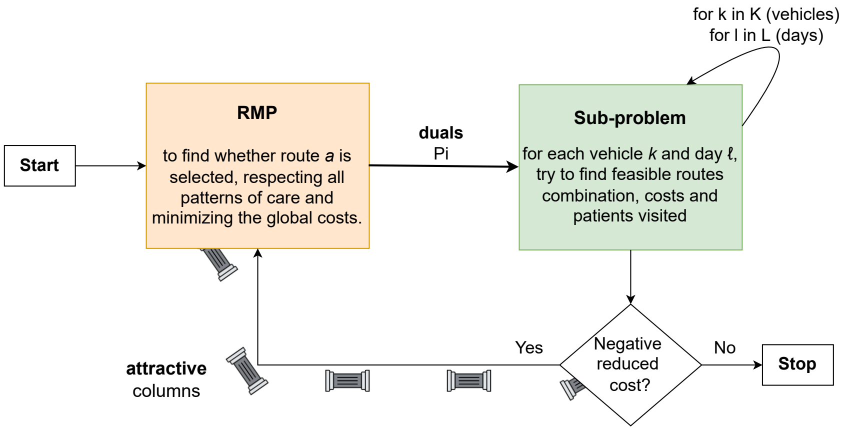

Figure 29: Proposed column generation approach.

process is repeated until there are no more attractive columns, i.e. there are no more new columns to be generated, and the approach ends.

Using the coding interface, preliminary computational experiments were performed implementing the CG approach. The computational experiments were performed on an Intel Core i7 10510U CPU 2.30 GHz 16 GB RAM machine. The CPU time was 60 (in seconds) on average until getting a result. The computational effort was much smaller to solve the same experimental dataset (instances with 15 patients), mainly when compared to the previous experiment using MILP and BB. In terms of the generated solution, this approach reached the same objective function value (473 kilometers) as the previous experiment, which represents the total distance to visit all patients and return to the health unit. Figure 30 shows the representation of the solution found in terms of the distance traveled (considered cost) for the vehicles available for home service routes. The solution illustrated the time horizon and the frequency of visits imposed by the patients (PVRP) as well as the sequence of visits assigned to the two vehicles in the scheduling.

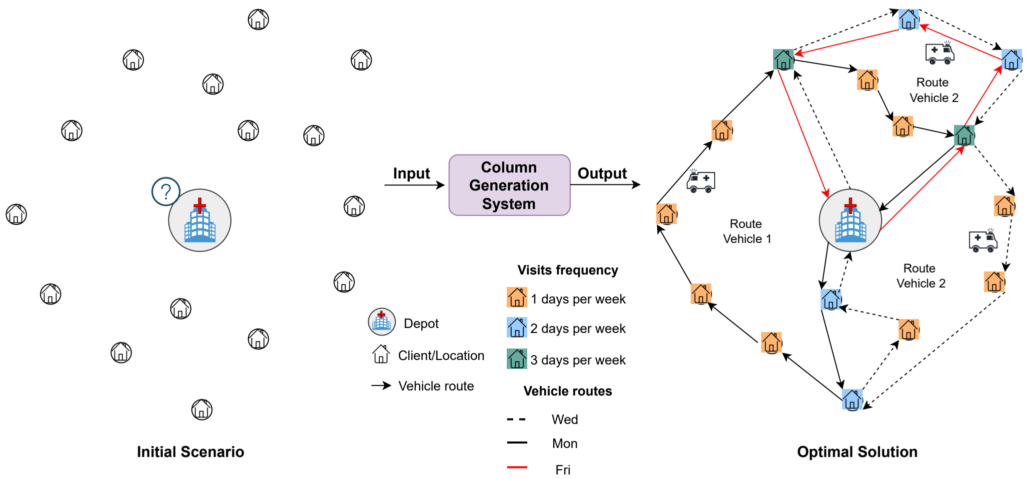

Figure 30: Column generation result.

These numerical results suggest that CG is a more efficient technique to solve the PVRP, which despite reaching the same optimal solution, the execution runtime was much faster, reducing the computational effort. It is important to note that the efficiency of the CG technique may depend on the quality of the initial solutions and the complexity of the sub-problem in generating columns. Furthermore, it should be noted that the solution time can be affected by factors such as the computational capacity of the machine used (the machine in this experiment was considerably superior) and the chosen programming language.

In summary, it is also important to note that the CG approach required considerable mathematical effort in modeling the problem and sub-problem variables. In the specific case of the sub-problem, it was an additional challenge since it was necessary to define a model that was capable of generating new columns efficiently and that respected the constraints of the original problem. However, investment in this effort may, in the future, bring significant benefits in terms of efficiency, economics and sustainability for the service, mainly solving more complex variants of the problem.

5.2 Single-objective Optimization

Regarding implementations using metaheuristics (namely using GA and PSO), three experimental validations were developed. The overall architecture of the HHC system using metaheuristics is similar to the three experiments and should integrate computational support, as shown in Figure 31. It should be noted that for the computational support, MatLab software was used for experimental dataset input and execution of algorithms. Furthermore, for all single-objective optimization experiments, the numerical results were obtained using an Asus laptop with an Intel(R) Core (TM) i7 CPU 2.2GHz with 6.0 GB of RAM.

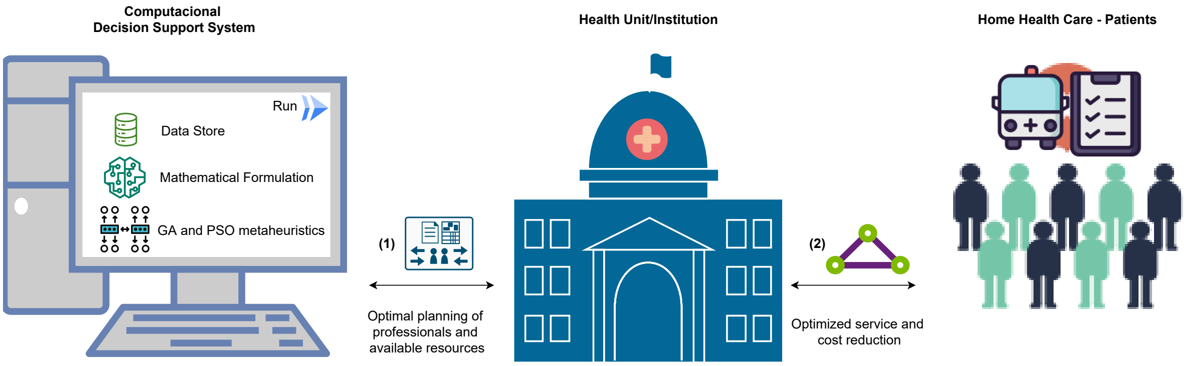

Figure 31: Decision support architecture design using metaheuristics.

Figure 31 is a possible solving approach for dealing with HHC using metaheuristics, in particular scheduling and routing problems (HHCSRP). In the center of the figure is represented the health unit, which has different exchanges of information (bidirectional) between the integral parts. The connections between the health unit and the computational support in order to answer to the scheduling and routing problems are represented in the figure by (1). The computational system will be responsible for storing the input data, formulating the problems mathematically and applying the GA and PSO algorithms. In turn, the optimal planning obtained is returned to the health unit. The connection between the health unit and the health professionals, and the latter with patients, providing the optimized solutions to support the team, is represented in the figure by (2). The health unit, in turn, will receive service efficiency results as well as satisfaction feedback.

5.2.1 Optimization of the Allocation of Nurses

In the works carried out by Alves et al. [15] and Alves et al. [25] the metaheuristics GA and PSO were implemented and validated in an attempt to perform an automatic and optimized nurse allocation for HHCSRP.The first work emerged right at the beginning of the thesis research, where the need to support decision-making, optimize and automate the HHC provisioning process became increasingly important for regions with low population density, as is the case of Bragança [15]. This need for computational support was due to the fact that until then the operational management of the service was planned manually, which almost always led to time-consuming and inefficient solutions. In this sense, particular attention was given to route optimization, scheduling and allocation of care workers to the service.

The research objectives were to schedule the care workers team, in order to determine the best solution that minimizes the time required by nurses to perform all home care visits. Thus, the final intention was to provide a better automatic allocation (planning) of the nursing teams, optimizing the workload balance, the time spent and, consequently, the costs involved.

The background of the problem, remember that this is a complex combinatorial problem where it is necessary to model and formulate several parameters, variables and sets (e.g., nurses, patients involved, treatments needs, locations, and times), the same ones presented in Chapter 3. In addition, some assumptions are considered, such as patient profiles, average duration of treatments, locations of all patients, among others.

In this sense, an approach was considered for representing the solution (in terms of output) that considered a vector X such that $X = (p_1, \ldots, p_p; nurse_1, \ldots, nurse_p)$. The vector X represents the allocation and scheduling, identifying the patient p_i who will be visited by the nurse $nurse_i$, for $i = 1, \ldots, P$.For a given X it is possible to define the nurse schedule and also the total time needed by each nurse to finish his/her work. Thus, the maximum time spent by nurses (T_{nurse}) to perform all treatments to all patients visited, including the return trip to the health unit, is the objective function of the optimization problem given by

$$minimize\ f(X) = \max_{Nurses} T_{nurse}(X) \tag{5.24}$$

The methodology was coded to apply to the computational system for decision-making of Figure 31 and the problems were efficiently solved by the GA and PSO optimization methods. These metaheuristics, explained in more detail in Subsection 3.2.3, are stochastic methods based on a population strategy inspired by natural social intelligent behaviors. At this stage of the research, practically all of the data present in the experimental dataset were used, where only the set of available vehicles was not included, since it was assumed that each nurse would use his own vehicle for home care visits.

In computational terms, the method seeks to optimize the problem 5.24 by iteratively measuring the quality of the various solutions. The algorithms and data input modeling allowed for the adjustment of computational parameters (stopping criteria, constant acceleration, inertia weight, initial population, mutation rate, crossover rate, among others), where for example, had some fixed variables, for both methods, such as the population of individuals equal to 30. Both methods used the same stopping criteria, limiting the number of function evaluations to 5000 or after 1000 iterations. Furthermore, GA and PSO had 100% success rate since the algorithm found feasible solutions in all runs [15, 25].

The numerical results showed that the minimum total time found by both algorithms is the same (260 minutes), the average of the solutions found is slightly higher in the PSO, and the number of times that converged to the best optimal solution is higher in GA. However, the average execution time to solve the problem is lower in PSO, because it finds the problem solution faster than GA (less than 100 seconds). Figure 32 depicts, as an example, the best obtained solution (in a gantt chart) by PSO. In the figure, P(1) - T.1 represents patient 1 who needs treatment 1.

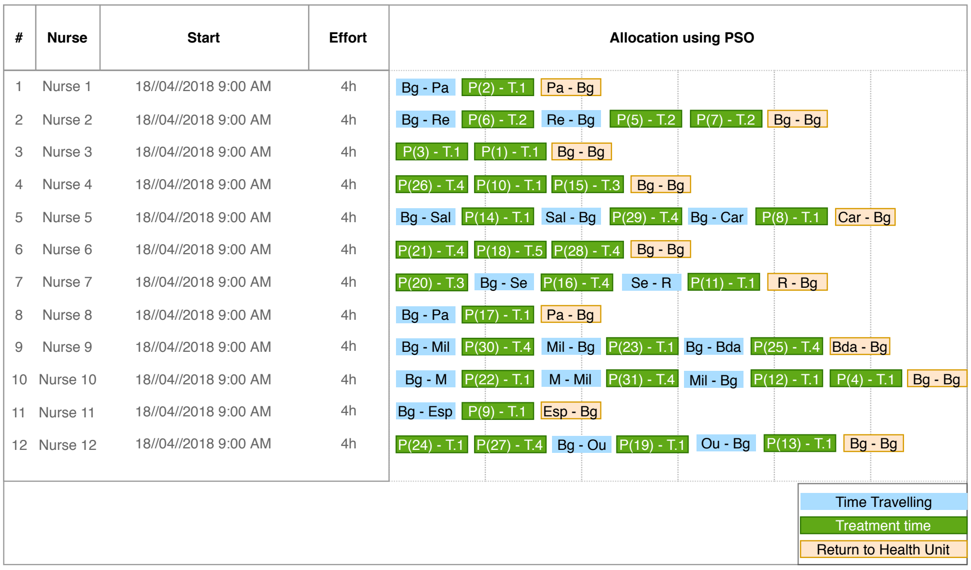

Figure 32: Automatic nurse allocation for HHCSRP [25].

The methodology showed that it was able to generate automatic allocations, with faster and optimized solutions. The results significantly improved and reduced the current process of allocating nurses to home care visits, that had an inconsistent schedule with an unbalanced workload. For example, the longest route that was practiced for the day of service in the health unit went from 369 minutes to 260, that is, a reduction of 109 minutes that allowed a quick replacement, a better workload balance and consequently a reduction in waiting time for patients.

In summary, these automatic strategies allow for minimizing the maximum time spent by each nurse on a home care schedule, providing better and more balanced solutions compared to those that were manually practiced [15, 25]. This approach represented a gain for all involved, health professionals, and patients, and boosted further studies, with the application of optimization methods in an individual and personalized way.

5.2.2 Optimization of Vehicle Route Scheduling

In the experimental work of Alves et al. [17], the goal is to plan the schedule and route of the home care visits, often created manually by the healthcare unit without any optimization support. Thus, in this work, there was a need to develop an optimization strategy to produce a daily vehicle schedule, reduce travel costs, and optimize the amount of time spent traveling. This effort attempts to implement an automatic schedule of home care visits (now considering the set of available vehicles) for the Health Unit of Santa Maria, using GA.

In the first instance, the problem took into account the experimental dataset and the number of tasks and processes assigned daily in the health unit. Regarding the experimental dataset, a normal scenario of home visits was tested, which included 31 patients (31 locations), 5 vehicles and related health professionals. Thus, a formulation was implemented that considered the notation of sets, parameters, variables and objectives associated with the problem and related to the general model of the Chapter 3. In turn, the solution was designed in terms of output, since it was considered a vector $\mathbf{x} = (p_1, ..., p_P, k_1, ..., k_P)$ where the patient p_i will be visited by the vehicle k_i, for

$i = 1, \dots, P$, and $\mathbf{x} \in \{1, \cdots, P\}^P \times \{1, \cdots, K\}^P$. For this $\mathbf{x}$ it is possible to define the vehicles schedule and the function $S^k(\mathbf{x})$, $k = 1, .., K$, that represents the total time needed to perform all visits of the vehicle k, considering the vector $\mathbf{x}$. The objective function ($f(\mathbf{x})$)is defined as the maximum time spent by all vehicles to perform all the visits. Then, the optimization problem is defined as:

$$minimize f(\mathbf{x}) = \max_{k \in K} S^k(\mathbf{x}) \tag{5.25}$$

which intends to minimize the total time needed to perform all visits. In order to solve this problem, the GA was coded, made from scratch. The parameter control values were adjusted to a suitable experience of the problem (e.g., used 30 individuals for the population size, $NFE = 5000$ for the maximum number of function evaluation and $NI = 100$ for the maximum number of iterations). In summary, 100 runs were performed (since GA is a stochastic method) and interesting results were collected. Figure 33 presents, as an example, the scheduling of vehicles for one of the analyzed days, with the end of visits occurring at the end of 498 minutes.

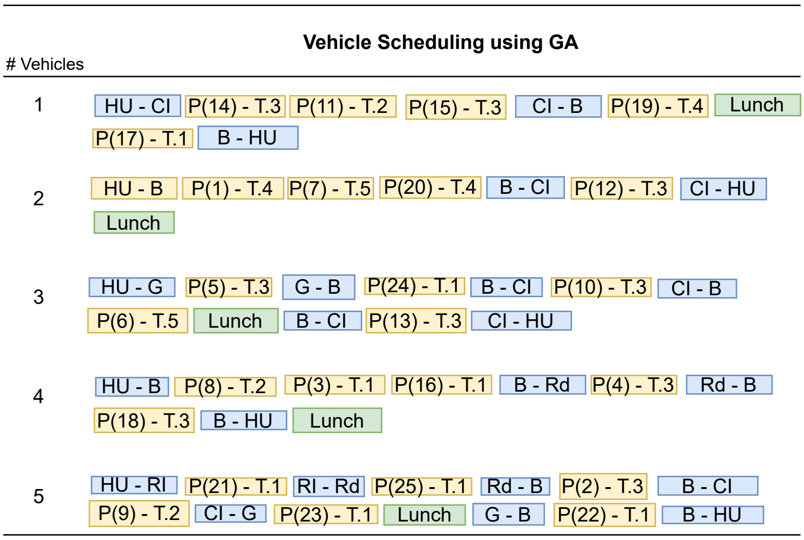

Figure 33: Optimal vehicle schedules using GA.

The blue color identify the travel time between locations (including depot) and the orange rectangles identify the patients to be visited and which treatments are required (e.g., P(1) - T.4 means patient 1 who needs treatment 4). In turn, the green color identifies lunch time.

The average execution time to solve the problem was always less than 30 seconds, quickly returning solutions with optimized values. The experimental results were duly validated and GA achieved 100% success rate in all runs. There was a significant reduction (approximately 30%) of the maximum time spent on providing the service when compared to planning in practice. Furthermore, despite the optimization and minimization of the operational visit plan, service quality was always considered, presenting gains for all involved. Moreover, the different schedules and visit routes are detailed in the published work [17].

5.3 Multi-objective Optimization

This section concerns implementations according to MOO approaches [21, 24]. These approaches have contributed to an automatic multi-criteria decision-support system that allows the optimization of several objective functions simultaneously, which are often conflicting.

Different strategies (methods) were tested and applied to the experimental dataset, which allowed the identification and examination of the different compromises between the objectives and demonstrated the importance of a multi-criteria approach to HHC services. In addition to their emerging growth during the COVID-19 pandemic, health organizations have discovered the need to optimize and reorganize their operations, taking into consideration multiple factors and priorities. In turn, the social dimension of the problem in question has an increasing impact on society, so investment and support for decision-making is a great motivation. This is typically due to the fact that home visits are scheduled manually, making it a time-consuming and challenging procedure that frequently results in an inefficient solution. In this sense, the operational limitations reveal that there is no computational support to optimize and determine the set of routes that consider (whenever possible) the time and distance to perform the home service and the number of vehicles available for scheduling the professionals. Thus, given the identified needs, the goal is to develop a multi-objective approach to the HHCSRP, according to a sustainable process of optimizing the routing and scheduling service based on the compromise between different objectives.

A healthcare facility must provide the schedules of all healthcare teams who perform tasks and have responsibilities, inside and outside the institution, on any given day, but may also require operational plans for the available vehicles. Urban areas have complicated socio-ecological systems since they have large land areas and difficult access to numerous villages and smaller regions of the city, as in Bragança, Portugal. The idea of these approaches is to generate computational mechanisms to optimize costs and available resources, increase performance and reliability for research in HHC, satisfy all stakeholders, and encourage operational competitiveness.

Figure 34 characterizes the purpose of the research, which presents the multi-criteria approach and ends with identifying and validating the Pareto optimal front, providing a set of benefits for operational management in a real environment.

The basic idea is to exclude the dominant solutions from the results to obtain the Pareto-optimal solutions. The representation method assists in validating Pareto-optimal solutions.

Thus, imagine a decision-maker wanting to optimize k objectives (sometimes conflicting). Without a clear preference for one over the other, it may have difficulty finding optimal solutions since it is facing a complex situation. In this case, it is important to mention that, when there are conflicting objectives, when improving one objective can negatively affect another objective. For example, reducing travel time for a home visit may negatively affect the cost of travel (e.g., through increased distance and/or costs of using the highway instead of rural roads). In situations where there are multiple objectives, there are likely to be trade-offs between them, meaning that improving one objective may come at the expense of another objective. Furthermore, when there are conflicting objectives in HHCSRP, such as cost, time, or unforeseen occurrences, the concept of Pareto optimality becomes crucial to represent trade-offs and improve the solution quality and response time (assist the decision-maker). Therefore, the investigation resulting from this section provides the development of two publications (one an international conference and the other a journal paper), which will be described below.

5.3.1 Experiment with two objectives

In the work by Alves et al., [24], a multi-objective approach to optimize the HHC problem using the Tchebycheff method (aggregation method) and GA is presented. The Tchebycheff method suggests using preferences information (weight vector) received from a decision-maker to find a set of efficient solutions. In the minimization context, the Tchebycheff approach has the form:

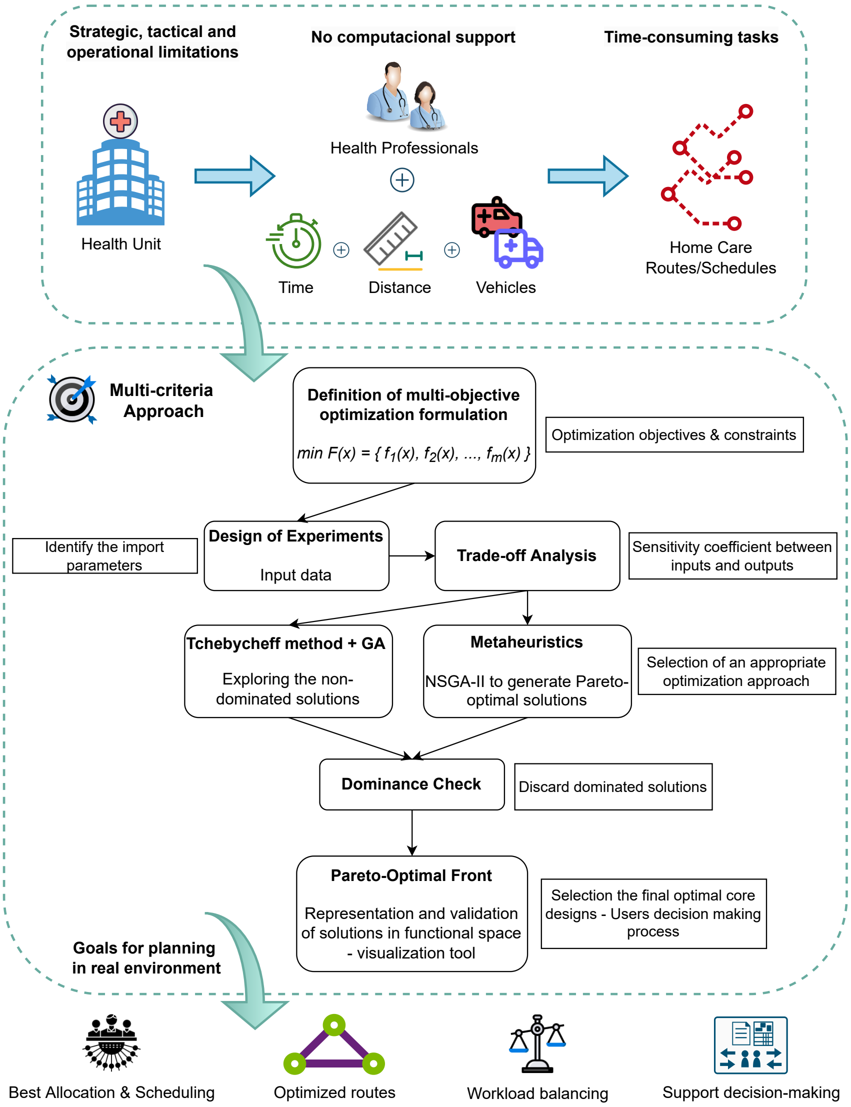

Figure 34: Identification of needs and multi-criteria optimization procedure for decision-making support.

$$minimize \;\; \max\{w_1(f_1(x) - z_1^*), \ldots, w_r(f_r(x) - z_r^*)\} \tag{5.26}$$

where $w = (w_1, \ldots, w_r)$ is the vector of non-negative weights and $z^* = (z_1^*, \ldots, z_r^*)$ is the ideal point in the objective space, that is, $z_i^* = \min\{f_i(x) \text{ such that } x \in \Omega\}$ for $i = 1, \ldots, r$. The Tchebycheff (or Chebyshev) scalarization method overcomes the flaws of the linear scalarization function, discovers all Pareto optimal solutions, obtains a better spread amongst the set of solutions and is not particularly dependent on the actual weights used [143]. In practice, this approach requires finding z^* by independently optimizing each objective function.

In this approach, the main goal was to reduce the time spent on visits and, at the same time, the cost related to the distance traveled, to assist the decision maker in the decision-making process. Thus, the multi-objective approach consisted of finding the set of feasible trade-off vehicle scheduling solutions that minimize two functions, $f_1(x)$ (time) and $f_2(x)$ (distance). Therefore, it was expected to define the Pareto front in the objective space and identify the best (or compromise) solutions.

In this sense, the multi-objective framework presented in Figure 35 (on the left) was designed and implemented, using Tchebycheff scalarization method combined with GA [24]. As previously mentioned, in the following framework, the vectors w and z^* refer to the weight vector and the reference point, respectively. The module "Multi-objective problem", which invokes time and distance objectives linked to HHC scheduling, performs the evaluation of vehicle scheduling optimization scheduling.

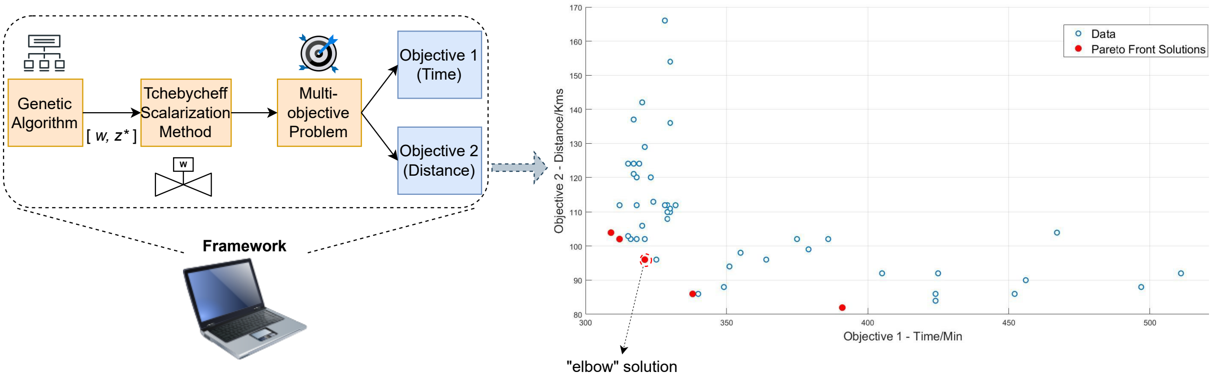

Figure 35: Design of the multi-objective framework and respective set of obtained solutions. Adapted from [24].

In this approach, an experimental dataset was used, considering 22 patients and 5 vehicles available to take health professionals to patients homes in order to perform the necessary treatments. The computational results, and the GA and Tchebycheff parameters, can be found in Alves et al., [24], where 10 runs were performed. The solutions obtained in 10 runs allowed, in a reasonable amount of time, the identification of optimal solutions on the Pareto front (on the right side of Figure 35). The red dots are non-dominated solutions and blue dots represent dominated solutions. An elbow solution was also identified (closer to the defined ideal point), as a suggestion to decision-making support, which could be particularly interesting for planning that wants to maximize the workload balancing between care workers and transport resources.

5.3.2 Experiment with three objectives

In the work of Alves et al., [21], experiments were carried out considering three optimization objectives and a personalized mathematical formulation, taking into account specific sets, constraints, parameters, allocation variables and transport availability.

Consider a routing network with defined a set of routes, whose parameters and constraints are already identified in Section 3.1. The HHCSRP optimization involved three objective functions that are described in the equations (3.3), (3.4) and (3.5). The goal of the three objective functions is to achieve, simultaneously, the minimization of the longest route (vehicle scheduling), both in terms of time (minutes) and distance (kilometers), as well as to accomplish optimization of the available (used) vehicles, by considering the details of the assumptions, sets and parameters. Taking into account the mathematical modeling developed and to guide and support the operational planning, an approach was developed to solve the HHC problem using an evolutionary MOO method, NSGA-II, combined with a Pareto-based approach.

In terms of a real-case scenario, the experimental dataset was again used to find and evaluate the different compromises between the objectives. The real scenario involved the 5 vehicles available for home visits to 22 patients (similar to work [24]). The information about locations allowed the creation of time and distance matrices between each distinct residential area. The assumptions also revealed some constraints, which affect the objective functions and limit time and distance in the domiciliary service, namely, 8 hours of daily work and 200 kilometers to be covered by each vehicle per day (estimated limitations for non-overload activities).

The simulations and experiments were run on an Intel(R) Core (TM) M-5Y71 CPU running at 1.4 GHz with 8.0 GB of RAM, using the *gamultiobj* function from the Global Optimization Toolbox of MatLab software. This function already offers powerful insights and is the variant of the elitist NSGA-II. The default values for the population size and the maximum number of generations were set to 50 and 500, respectively. Due to the NSGA-II behavior, 30 independent runs with a random initial population were carried out, and the maximum number of generations was used as the stopping condition, which was set at 1000. Since the Pareto proportion is 0.35 by default, specific solutions are discovered for each run (0.35 × population size).

The results and discussion of the optimization of the multi-objective approach involve constructing the Pareto optimal front and finding the set of feasible trade-off solutions to facilitate the decision-maker in choosing his/her best option. In this sense, Figure 36 illustrates the sustainable procedure adopted so that from the application of the multi-criteria approach in a), the general set of solutions is obtained in the objective space b) and from then on the user has the ability to obtain support for decision-making (parts c) and d)). Thus, as depicted in Figure 36 in part b), it is possible to use graphs to represent and visualize the Pareto front (optimal solutions when the three objective functions are optimized simultaneously). The blue dots represent all the solutions identified among the 30 runs, while the non-dominated solutions were recognized with a red circle. Furthermore, for all intents and purposes, it should be noted that the solutions were obtained in a reasonable time, never exceeding 1 minute.

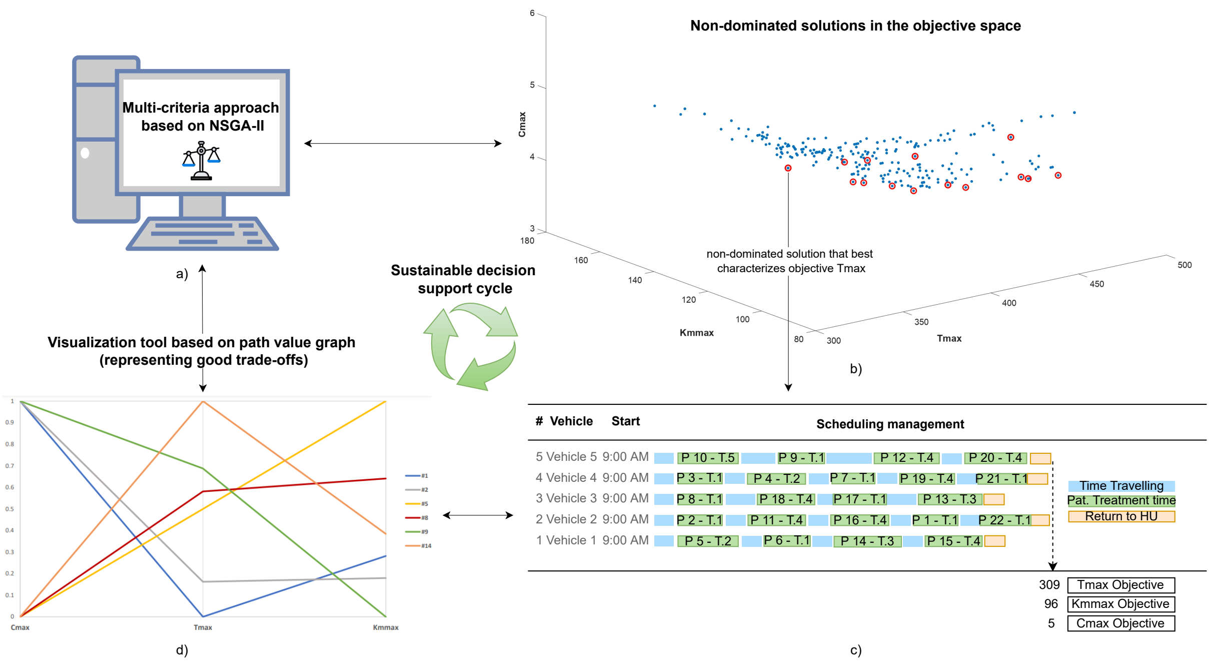

Figure 36: Sustainable decision support system, considering the multi-objective approach and its results.

The positions of the non-dominated solutions (14 solutions) express the compromises between the objectives. These solutions must be analyzed since they are the most interesting in terms of the objectives, and each one presents a trade-off that must be carefully explored. It is also possible to notice that only solutions are obtained for the objective $Cmax$ (objective in (3.5)) with 4 or 5 vehicles. This is due to the fact that solutions with less than four vehicles would exceed the imposed and estimated constraints that regulate the health unit. In addition, a non-dominated solution (that best characterizes the $Tmax$ objective, but just as an example) was chosen and represented (gantt chart at part c) of Figure 36) to discuss trade-offs between the objectives and identify the solution features. This solution concerns the extreme point and presents a good workload balancing among all vehicles.

Finally, it was possible to generate a path graph value, which could assist the decision-maker with better knowledge and understanding of the problem. This visualization tool, part d) of Figure 36, details the trade-offs between objectives. It was necessary to normalize the values of each function so that it would be possible to adapt the scales to build graphs that objectively aggregated all the information.Thus, a clever selection of the most interesting solutions from the set of non-dominated ones was generated, which include, for example, extreme points of the Pareto front, “elbow or knee” solutions (shortest distance to the ideal point), among other features that help to reduce the analysis space. Thus, 6 solutions were selected, representing points of faster change between the objective functions and giving the decision-maker a sense of where there might be a useful compromise solution. Standardized target values for different trade-offs are represented by horizontal lines. This visualization tool guides the decision-maker to implement better policies in the HHC service and benefit from this computational assistance.

The developed sustainable decision support cycle allowed simplifying and optimizing scheduling management and route allocation with very fast responses. Furthermore, the solutions were validated by the Health Unit and showed savings ratios of approximately 30%, both in time and distance and in the balance of workload between vehicles. Additionally, this work provides several efficient solutions that have been standardized, tested, and compared to current practice (manual solutions with time-consuming tasks) in terms of the suggested strategy. The findings highlight the importance of a multi-criteria approach allowing to assume responsible characteristics in operational terms and sustainability of a HHC service and its community.

In summary, the non-dominated solutions provide interesting insights for choices considering user preferences, benefits and trade-offs, reducing transportation costs and resource allocation times, which can help the National Health Service invest the savings in other healthcare sectors.

5.4 Multi-agent Systems

This section describes the implementation and experiments of a specification for distributed scheduling in HHC through a MAS and using the framework JADE [14]. The scheduling and assignment of tasks becomes a huge and complex challenge in the operational planning of the health service due to uncertain demand, optimal allocation, and/or travel restrictions.

HHC services present a lack of distributed knowledge, need for coordinated effort, and are complex problems due to the large amount of dispersed information. In this sense, opportunities arise to decentralize solutions with intelligent systems that distribute computational effort and guarantee flexibility and fast responses. Thus, MAS provide smart techniques to coordinate a socialized solution to achieve the HHC service goals, even in emergencies.

In the experimental research work by Alves et al., [14], the main goal was to specify a distributed MAS that intends to manage the HHC service with more capacity to get fast scheduling solutions, even in the presence of dynamic situations. Furthermore, an experimental scenario was used to generate automatic and personalized task allocations with improved responsiveness for multi-criteria assessment.

This work focused on designing and implementing an architecture for distributed scheduling considering an innovative specification of a MAS responsible for simplifying through fast and intelligent decisions. The architecture will be described in 3 steps where the first concerns the MAS entities and behaviors, the second concerns the interaction of the agents and the third and last describes the functionalities of the agents in the allocation process.

Specifying the MAS entities and behaviors, the attainment of solutions was designed taking into account the interaction between a network of 2 types of agents (the patient agent and the health professional agent, each with different responsibilities) in the multi-agent layer. Figure 37 presents the three layers of the architecture with emphasis on the multi-agent layer, but not forgetting that the rest complement each other in an integrated system to contribute to scheduling, resource allocations and routing applications, with a special focus on HHC studies.

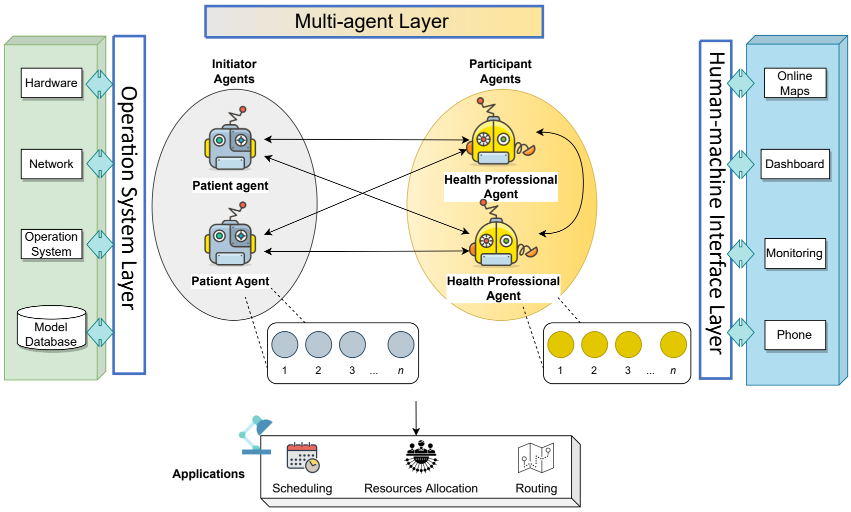

Figure 37: MAS-based system architecture for distributed scheduling. Adapted from [14].

Considering the agent's network, for example, the Patient Agent has the ability to start the negotiation, initiate the call for proposals, set the parameters, and make the selection of the best bid/proposal. On the other hand, the healthcare professional agent has the skills to perform the services/treatments that are needed, respond to calls for proposals, and make a bid.

As previously referred in section 4.2.2, the distributed scheduling emerges from the interaction between the agents (in this specific case patient and health professional agents). Regarding the interaction of the multi-agent layer, the ability to negotiate between patient and health professional agents was designed and specified following a custom protocol based on CNP. This specialized protocol supports interaction and message exchange between agents and their environment, in an attempt to cooperate and negotiate the best solutions, optimizing, whenever possible, the internal goals. Still on the agent's interaction step, after some patient agent activates the CNP and performs a *cfp*, the health professional agents will handle the task proposals by performing a matching protocol (see Figure 38).

The idea of this synchronization in matching is to assume that when a patient tries to assign a certain task (e.g., a necessary treatment), some agent of the health professional has the capacity and skill to execute it and is available (perform the service/treatment), and the matching is obtained, which causes the health worker to make a proposal. In this sense, if there is a match, the system allows to calculate a price and make an offer to continue the CNP. On the other hand, if there is no match, the health professional agent sends a rejection message.

In runtime (after and/or during the scheduling), if there is an unexpected event (new order, delay or failure of

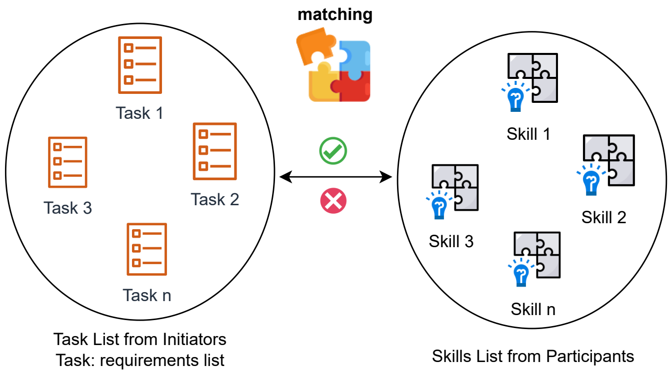

Figure 38: Task request and response matching protocol based on skills and resources.

the health professional), the patient will be notified and start again to request a new allocation with available health professionals, that is the CNP will be restarted.

Regarding the functionalities of agents in the allocation process (step 3 of the MAS architecture), the main idea is now to apply intelligent capabilities to make decisions, namely, price calculation with workload-balancing and evaluation of proposals.

Thus, the final value of the proposal, designated in the literature as cost or price, is calculated based on a multi-criterion approach. The price function establishes the value, for instance, based on two elements: the fixed costs and the profit margin. Fixed costs are the costs required for a certain execution or order, while the profit margin is the amount that must be adjusted to reflect current market laws. The $price$ to be proposed by each health professional agent i to perform some task (treatment) is calculated using the following equation (5.27):

$$price(i) = \frac{C_i * T_t + [C_i * Time + C_{ci} * Distance]}{100} \tag{5.27}$$

where C_i is the cost of the healthcare professional per hour (execution cost), T_t refers to the cost of the duration of treatment that needs to be done, $Time$ refers to the distance time involved in the visit route, C_{ci} identifies the fuel costs and $Distance$ comprises the distance involved in the trip back to the health unit. These parameters were selected because they cover the main aspects that affect the cost and efficiency of a HHC service, namely in terms of availability and allocation of resources, required treatments as well as travel times and/or distance of routes. Also, it is possible to have dynamic price where the margin may increase or decrease according to the allocations already made. Agents can reduce the price if the bid acceptance rate is greater than one or increase if the price contributes to the balance of workload.

In terms of evaluating and deciding on the best proposal, elaborated by the patient agent, two strategies can be combined. In the simplest one, the patient agent selects the proposal considering only the final price, that is, it can choose the proposal with the lowest or highest price. The more complex strategy combines a multi-criteria function, where the agent will analyze different parameters with different weights considering the preferences of the patient, such as, the proposed price, the trust/reputation, patient preference in the health professional, among others. The expression can be analyzed in Equation (5.28).

$$ScoreRate(i) = \frac{1}{100} \sum_{i \in N \setminus \{0\}} W_i C_i \tag{5.28}$$

This strategy is the most interesting to support the patient in decision making, where i is each of the proposals and W represents the weight of trust given to the criterion C (e.g., price), etc. It is important to keep in mind when analyzing the recommendations that the prices of the multi-criteria must be normalized in order to standardize different intervals. The fact that the several criteria must go in the same direction, i.e., either maximize or minimize, is another crucial consideration, since the best proposal must be selected.

Due to the fact that many of the health professionals' agents have similar knowledge and skills, the probability of offers with the same value was taken into account when choosing winning bids, particularly in the initial call for proposals. Due to this, the first come first served (FCFS) rule was implemented, which states that the first offer received from equal offers is accepted in cases when a decision must be made between proposals of equal value.

In this implementation of MAS, it was decided not to use the real data from the experimental dataset, but to simulate a set of patients distributed in a HHC unit in the district of Porto in Portugal. This dataset change can be justified by different needs and objectives of the study, since the simulated case study in another region of Portugal, in a less comprehensive area, would allow a more careful analysis to provide relevant preliminary insights for subsequent real application. In addition, there was a need for controlled experimentation, in a simulated environment that facilitated the evaluation and comparison of different approaches, which in a real dataset would be unfeasible or impractical. So, this simulated dataset is just an example, because it can be easily replicated in other regions and organizations. The simulated data involves 10 patients distributed in an area of 50 km^2, with two different types of treatment, and 3 health professionals. Some patients require more than one treatment due to need-to-need tasks that would precede other treatments (e.g., task 2 after completing task 1). On the other hand, each healthcare professional, based on cumulative skills, may not be able to perform all treatments (some may be more specialized and others may not). Furthermore, the price calculations (based on distance and time) in the proposals are dynamically instantiated using the Google Maps cloud, which provides locations and routes with real-time values.

In terms of preliminary implementation and results, the MAS system was implemented using the JADE framework and the personalized CNP based on FIPA protocol. The experiments were conducted on a Huawei Matebook, with an Intel(R) Core(TM) i7 CPU 1.80 GHz with 16GB of RAM. The results are summarized in Table 6 in terms of percentage of allocation (that allows to verify the resource allocation distribution) and the makespan (time to complete the several allocated tasks).

Table 6: Summary of experimental results in terms of allocation and scheduling using MAS.

Agents	Allocation (%)	HHC schedule (minutes)
Health Professional #1	40	163
Health Professional #2	30	135
Health Professional #3	30	145

The treatments were uniformly distributed by the health professionals (see allocation percentage column) which is a very important aspect to be considered in this kind of problems. In terms of results, for example, the health professional agent #1 was assigned a total of 4 patients, and his schedule ended after 163 minutes (which comprises the execution of the treatments, the travel between patients and the return to the health unit). The specified system had efficient scheduling solutions, with the treatments requested to be distributed and properly allocated to health professionals, respecting their precedence, and looking for workload balancing.

The previously implemented work can be seen in more detail in Alves et al. [14]. In terms of the performance of the assembled system, each solution (simulated HHC schedule) has specific quantitative and qualitative results. The quantitative results showed that, for example, the registration of agents, followed by the interaction and result information, had a maximum response time of 2 seconds. In addition, performance and productivity were obtained in case of failure, with instantaneous interactions and clear responsiveness, especially when new request task eventually emerges in the system. In turn, the qualitative results allowed to verify good scalability, because there was no need to change the implemented code, it easily went from 13 to 100 agents and the system worked, with high modular capacity. Furthermore, the system proved to be robust in critical domains, since the injected disturbances implied that a specific agent was not attended to participate in the scheduling process, but all the other agents worked correctly without interruption.

In summary, the results demonstrated allow to emphasize once again that the HHC scheduling and/or routing process requires modernizing its system, using dynamic, fast solutions and reacting to condition changes. For this, MAS solutions offer a new way to design these systems based on the interaction between individual agents, and in this work it was possible to verify personalized and high-level solutions that can be replicated in an operational context of HHC. Furthermore, the MAS architecture specification highlights the qualitative and quantitative aspects, namely the experiment response time, productivity, robustness, and scalability.

In general, this experimental validation allowed designing and specifying a module MAS (with well-defined processes of personalized interaction and negotiation) with collaborative potential in a future prototype, the ability to combine centralized and distributed approaches and involve a health organization in the decision process.

5.5 Hybrid Approaches

Traditionally, scheduling systems use centralized approaches, where all activities and resources are controlled by a single decision-maker (e.g., heuristics). However, these decision support systems are mostly static, less responsive to emergencies, inflexible, and do not consider unexpected events. With decentralized approaches, scheduling can be received in a distributed way, using dynamic, fast, and optimized responses, increasing system responsiveness and rescheduling capabilities. Recently, it has been studied how ICT can be the basis for interacting with different interconnected and even decision-smart objects. In this way, challenges have arisen for new solutions that do not yet use decentralized approaches in hybrid application results, where MAS and optimization methods are employed for this specific design [10]. The goal is to demonstrate the theoretical concepts of Chapter 3 (MAS and optimization methods) that will be applied in a combined (hybrid) way to apply in practical cases (such as HHC). The results and experiments will be important to validate the constructed hypotheses, contribute to highlighting the benefits and effort distribution in complex tasks, and improve flexibility and usefulness for real-time scenarios and reactive environments.

5.5.1 Hybrid Approach in Industrial Environment

Firstly, and since hybrid solutions are an incentive to explore multidisciplinary areas, there are already some results in the manufacturing context, where for example, some preliminary studies were carried out to explore these distributed approaches, namely the combination of AI and OR. Thus, two of the initial approaches were intended to design a computational support system capable of simultaneously supporting distributed scheduling and layout planning, considering a module for dynamic adaptation using MAS combined with another optimization module using GA and

PSO [5, 11]. Both approaches, in certain industrial environments, such as manufacturing, are increasingly and importantly used strategies. While human intervention is still necessary for manufacturing, Industry 4.0 is pushing toward a distributed approach to data generation, optimization, decision-making, and supervisory control. The integration of manufacturing and management processes, such as scheduling, is critical. For example, the job shop scheduling problem is a well-known optimization problem that can significantly impact efficiency and productivity. For this, dynamic scenarios with possible disruptions or new orders, improving the work in process, the utilization of production resources, and adaptation with the minimal human intervention were considered, in an attempt to prove the theoretical concepts of the areas under study. In addition, it generates automatic decisions that can be deployed in real environments to integrate problems in an interactive and user-friendly way, incorporating decision factor testing and dynamic rescheduling alternatives to support decision-making.

Briefly, the methodology began by setting up a dynamic and flexible manufacturing system, with the possibility of creating different products (jobs) [5]. Different types of the processes (operations) were also considered and executed until reaching the final product. Each set of operations can be performed on a set of machines, which will be responsible for completing the manufacturing operations, requiring a processing time. It is important to note that, there may be machines capable of performing/completing the same operation, while others will have more specific responsibilities.

Although they may seem different at first glance, HHC and manufacturing issues may share some similarities, especially regarding the optimization of resources and processes. For example, in both cases, efficient allocation of resources is necessary to maximize productivity and minimize waiting time. In the case of HHC, patients must be seen by qualified nurses or care workers, and home visits must be efficiently planned to meet the needs of each patient. In the case of manufacturing, machines must be properly programmed and tuned to perform specific operations and produce final products efficiently. Additionally, both HHC and manufacturing can benefit from applying these hybrid approaches to efficiently optimize solutions and allocate properly the resources.

Figure 39 illustrates the problem taking into account the layout scenario to be considered and its relationship to HHC problems. The work considers some constraints on the scheduling assignment, such that: the products are independent, and there may be priorities between them (e.g., completion); each machine processes only one operation at a time; all jobs are available simultaneously at time 0; there may be a precedence of operations; after operations are completed on one machine, the job moves on to the next (or terminates); and will be considered disruptions during the processing of jobs.

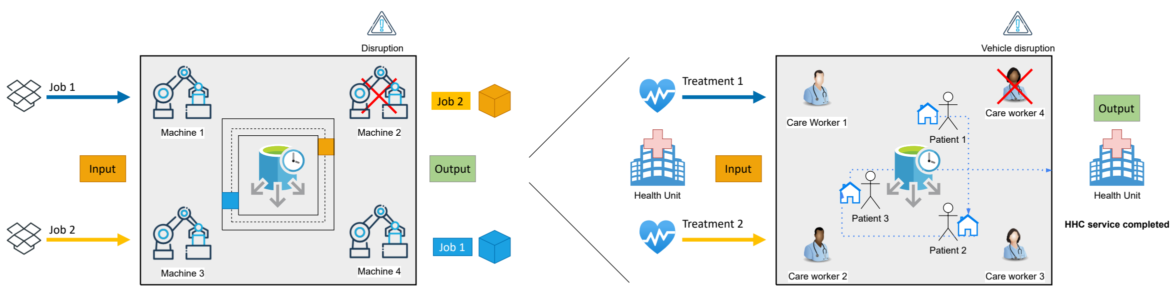

Figure 39: Encoding scheme and layout variants. Adaptation of the case study for HHC. Adapted from [5].

By relating these characterizations to HHC, some similarities can be identified. For example, as with manufacturing constraints, care workers and nurses in HHC must deal with independent patients and treatment priorities. Furthermore, just as machines in a manufacturing environment perform one operation at a time, care workers or nurses in HHC need to manage their tasks efficiently to ensure that each patient receives the necessary treatment without unnecessary delay. It is also important to note that just as interruptions can occur when processing jobs in manufacturing, patient emergencies or vehicle problems can disrupt scheduling and routing in HHC. In addition, the previous figure sought to relate what the implementation in manufacturing can and allows to relate (e.g., machine resources) with the main case study of the thesis, the HHC service.

In this sense, the challenge is to find the jobs scheduled on the machines while taking precedence restrictions into account in order to minimize the batch makespan, i.e., the finish time of the last operation finished in the schedule. The major question was whether the sequence of the jobs affected the optimal time. This requires solving the problem several times, with the difference becoming the order of the jobs.

The system framework comprises a scheduling system that combines offline and online modules that may deal with the two sub-processes sequentially: efficient planning using optimization methods and real-time responsiveness solutions using MAS [5, 11]. The two modules can exchange information, balancing decision-making based on requirements. One module optimizes the scheduling of jobs that run offline for a certain condition under evaluation (centralized using GA and PSO). The other module is concerned with dynamic agent-based (re)scheduling in reaction to disruptions or changes in conditions, such as a damaged machine or another failure. Agents (representing jobs and machines) have the ability to negotiate scheduling tasks autonomously without minimal human intervention. The online module, in addition to containing the MAS approach, includes the simulation control dashboard and management of setup and output data (similar to the one presented in the Section 4.2.3).

As for the experiments, the online dashboard and the agent-based model were implemented in NetLogo [193], an excellent platform for modeling and simulating dynamic models in agent-based systems and which allows connection via the TCP/IP protocol[2] for communication between other networked tools (sharing of optimization inputs and outputs via MatLab). In the simulation, the admin would have the ability to specify the problems, that is, initialize variables, set parameters, include restrictions (e.g., number of iterations) and transmit these data to the optimization module. Likewise, when the optimized result is obtained, it will be forwarded through the output viewer and represented in the control panel. Monitoring would be constant, and the admin would ultimately have the ability to test the system in disruption environments, enabling the dynamic module to reschedule and behave autonomously. Finally, the trade-off between centralized tool and dynamic interface allows for simple manipulation and handling by the independent user.

The data used in this manufacturing system were gathered from an industrial data set from an AIP-PRIMECA cell at the University of Valenciennes, which allows the generation of different products (jobs) [196]. The formulation and implementation aspects of the problem, dataset and computational results can be reviewed in more detail in the following works: [5] and [11].

These papers propose a hybrid system that simultaneously simulates and solves job shop scheduling in a manufacturing layout scenario with unexpected events. The approach aims to support and customize smart and/or optimized solutions (under machine disruptions) and enable users to interact with the system to properly adjust priorities or refine setups or solutions, in an interactive and user-friendly way. Thus, in today's competitive manufacturing contexts, companies may improve flexibility and efficiency through flexible manufacturing systems and just-in-time production, as well as add strategies and dynamics to improve quality, time, and profits.

[2]TCP/IP is a set of communication protocols between networked computers. TCP is the Transmission Control Protocol and IP is the Internet Protocol.

5.5.2 Hybrid Approach in Home Health Care Environment

Taking into account the particularities of previous experiments in the context of manufacturing and their relationships with the HHC service, the following experiments are preliminary results of two hybrid approaches applied to the domain of health [19].

5.5.2.1 Metaheuristics and Multi-agent System

HHC managers need decision support systems capable of solving large real-world situations and providing good solutions. On the other hand, MAS allows for the decentralization of control over distributed structures, providing robustness and autonomy in such systems.

Thus, a hybrid combination of optimization features with responsiveness provided by MAS solutions was worked on [19]. The objectives of the work were to generate a control system in a network of agents, with dynamic behavior, in autonomous decision-making, capable of carrying out alternatives to modify behavioral rules and capabilities to adapt to emergence or disruptions without external intervention.

The work considered the problem of assigning tasks outside the health unit, with the aim of minimizing the travel time used by vehicles to perform all home visits (a situation considered disruption). For this, some assumptions were taken into account, namely the time matrix of travel between all localities, the number of patients who need home care services and who were assigned to a working day, the list and duration of the treatments, and finally that all trips started and ended at the unit.

The architecture of the created system was essentially based on the integration of two modules, one offline and the other online (which contained the simulation dashboard in the NetLogo software [193]), as illustrated in Figure 40.

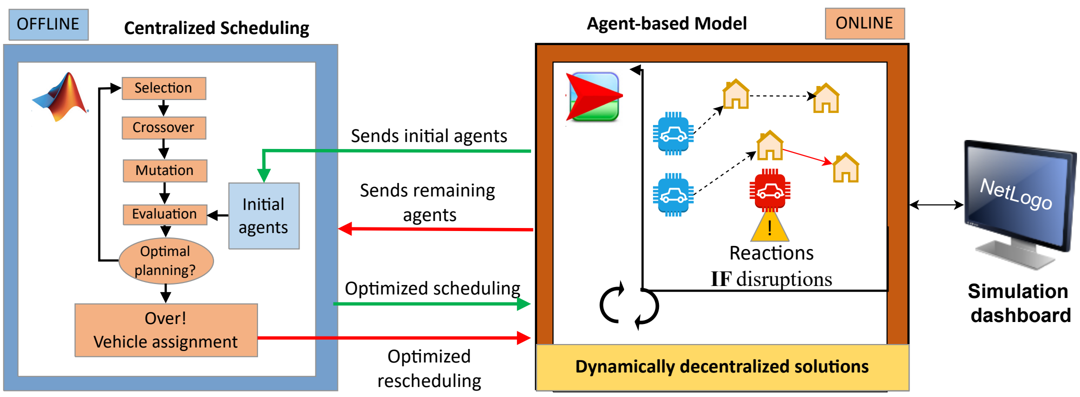

Figure 40: System architecture. Adapted from [19].

The module on the left performs the optimized scheduling for the vehicle routes, running offline. In this module, GA will be used in an optimization problem similar to the one presented in 5.2.2.

In the online module, it was possible to start the system, send the initial agents according to the problem instances and data, initial population, and optimization parameters, and in turn receive the optimized scheduling of the routes. Furthermore, the online module concerns the dynamic re-scheduling (by agents interaction), in response to disruptions or condition changes, e.g. a broken vehicle. Regarding the behavior of the agents, two types of agents were coded, patient agent and vehicle agent. Regarding the behavior of agents, two types were implemented: passive behavior and autonomous behavior. The first is characterized by vehicles carefully following the optimized route planned from GA and provided by the offline module to minimize travel time. With the autonomous behavior, the vehicle follows the planned route, but is able to dynamically adapt the schedule in case of disruptions (through the interaction with other vehicles that are represented in a MAS). Figure 41 presents the interaction patterns between agents, in an attempt to obtain the best performance criteria and greater autonomy in coordination of disruptions for real scenarios.

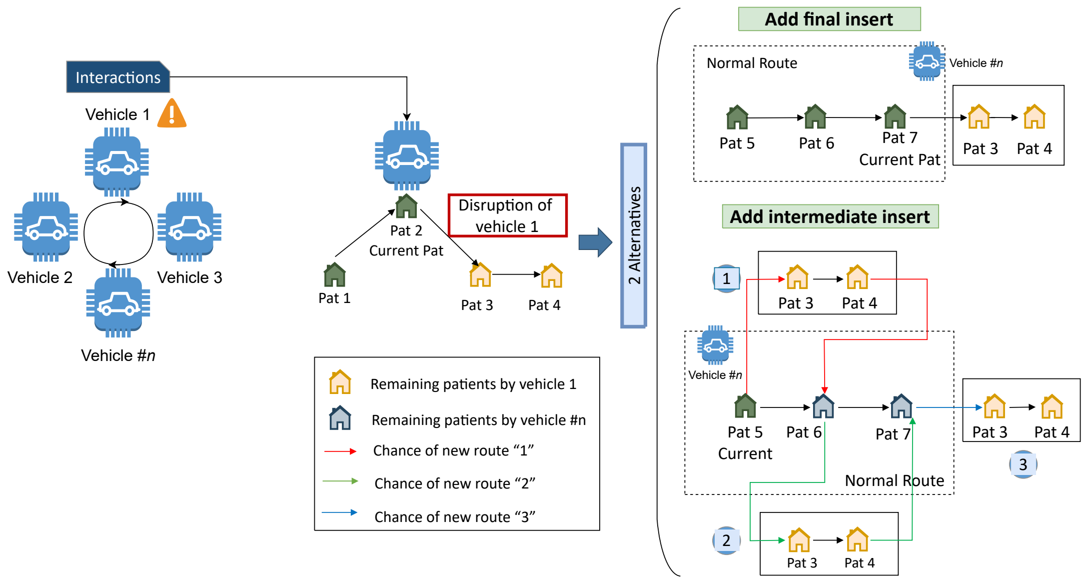

Figure 41: Interaction patterns and alternatives methods for decision. Adapted from [19].

The interaction patterns in the autonomous behavior refer to the dynamic procedure that involves decisions that are considered to help a vehicle in the event of disruption (which becomes unavailable). The interaction pattern is based on the CNP protocol, where the initiator (e.g., vehicle disrupted) scans the agents list and checks if there are moving vehicles available to take over the remaining route. For each available vehicle, check the time between the current or final patient on its route and the first patient on the remaining route left by the initiator (appointment). If some of the participants on the route are not available or have already completed their route, a spare vehicle can be used. To verify the conditions to take over and attach the remaining route (decision factor), 2 alternatives were developed based on the comparison of the shortest distance and time between the remaining route and the next or final patient of the available vehicle route (on the right side of Figure 41). The code always searches for the best total route proposal (the vehicle route available + remaining route) with the most optimized time and cost.

In this way, the simulation experiment protocol was followed, where the agent-based model was implemented. The agent-based model is connected with MatLab (through an extension) to allow the exchange of the optimized scheduling solution and to transmit any valid command from MatLab to NetLogo and vice-versa. Figure 42 illustrates the simulation dashboard.

The interface is based on a set of steps, which starts with the generation of patients from a random selection of the experimental dataset. Next, the scheduling is performed by the user, and finally, the vehicle routes sequence is displayed, where it is possible to update the dynamic reschedule by agents in their autonomous behavior. The simulation tool was applied to test and experiment a scenario from the dataset, which included only 15 patients within an area of approximately 50 km^2 from the Bragança region, and allocated the 5 vehicles.

In terms of the simulation results, GA, had 100% of successful rate since they found a feasible solution in all

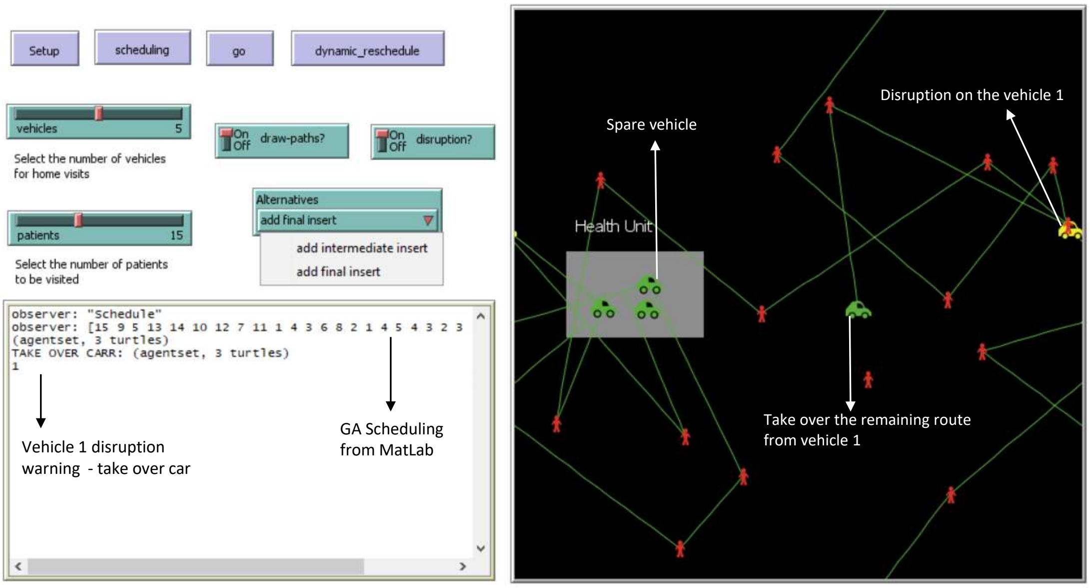

Figure 42: Simulation in the NetLogo interface. Adapted from [19].

implementations. In addition, the total route obtained by the GA, is obtained extremely fast, that is, it only took 24 seconds. Furthermore, Figure 43 shows the solutions of the routes obtained by each alternative, also considering the eventuality of a disruption.

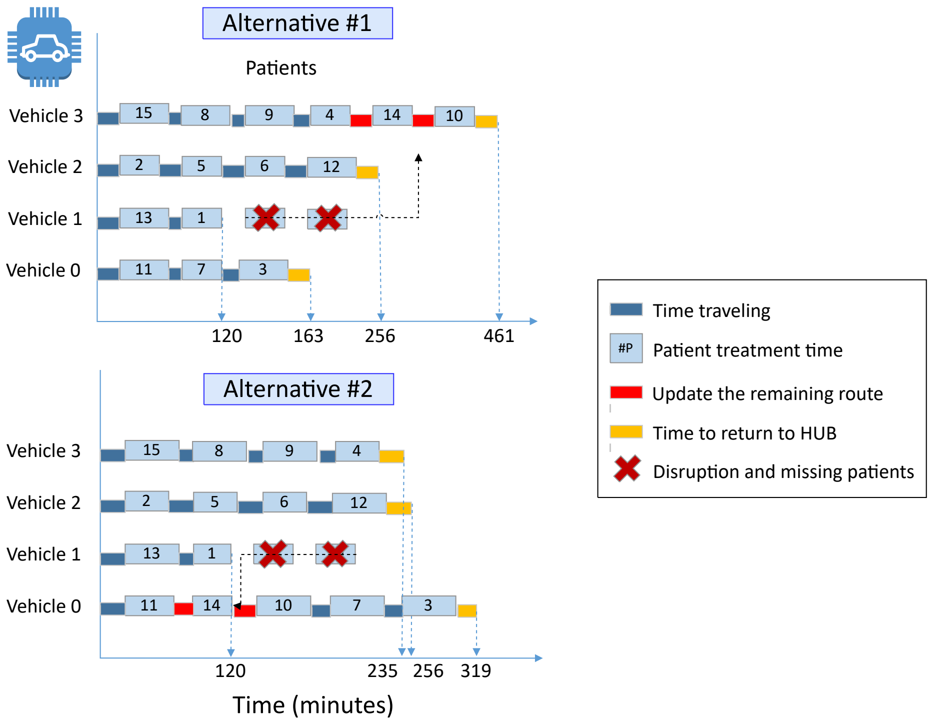

Figure 43: Routes simulation based on proposed alternatives. Adapted from [19].

It is possible to verify that vehicle 1 was the one that suffered the stop or failure, leaving to visit patients 14 and 10, respectively, that is, it will be our remaining route. The remaining route has been included in different vehicles depending on the alternatives. Alternative 2 allowed a significant reduction of 1 hour and 10 minutes compared to alternative 1.

The simulation benefited from a flexible framework in obtaining optimized solutions, increasing their applicability, provide task effort distribution, reduced resource impact, and finally, the quickest and most accurate response to changes or interruptions caused by agents. In addition, the objective was to highlight the efficiency of the proposed decision factor defined by the ability to minimize the vehicles travel time and automatically test and optimize disruptions or failures in vehicles, in an autonomous and intuitive way.

5.5.2.2 Exact Method and Metaheuristic

A hybrid approach involving an exact method and GA is presented [6]. This experiment involves innovative solutions to a real routing and scheduling problem in different instances (scenarios) from the experimental dataset. It was necessary to describe a problem statement in which different general properties, constraints, and/or assumptions were considered for the problem: the planning process of the Health Unit, geographic area, resource dimension, and fixed parameters (care workers, characterization of the staff, number of patients and treatments/services they need, and patient locations), already defined in Chapter 3.

The implementation was tested for the entire experimental dataset, generating 9 cases of different instances (sensitivity analysis to the output of a set of different instance sizes), varying the number of patients, nurses and respective locations [6]. This approach involved the implementation of a MILP model in the optimization programming language (OPL), using CPLEX and BB, with default parameters and with an additional stopping criterion based on the execution time limit of 3600 seconds. Furthermore, the metaheuristic GA already implemented and coded in MatLab, was used. The computational results were obtained from a machine with an Intel(R) Core(TM) i7-10510U CPU processor of 2.3 GHz and 16 GB RAM. Thus, the idea was to perform an initial run of the GA to obtain a good solution quickly, and from there, give it to the exact method, making a feed within the MILP model to reduce its search space and reach the optimal solution faster (called *warm* start). Figure 44 represents the described approach and the visualization of the experimental results in terms of boxplots.

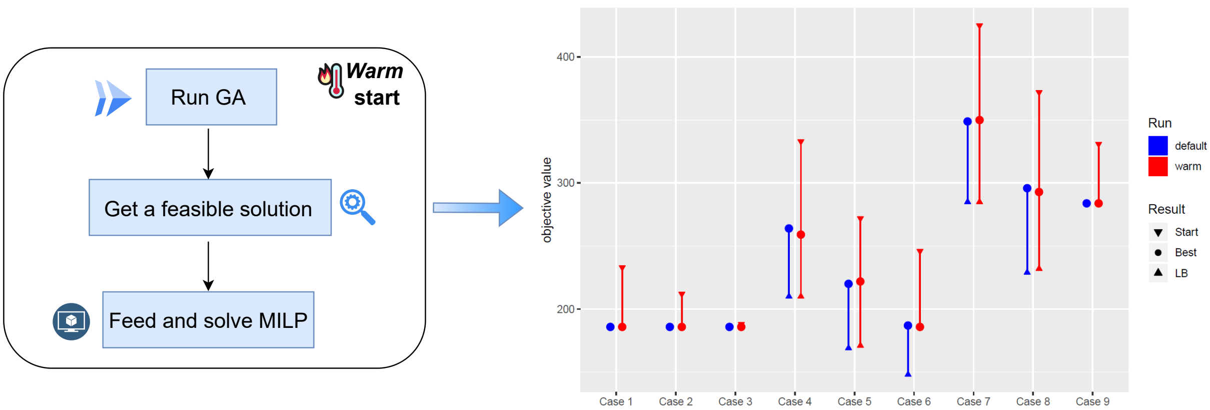

Figure 44: Hybrid approach that compares MILP, GA and a *warm start* that combines the two. Adapted from [6].

The results have some variability (changes relatively to *default* CPLEX), and drawing definitive conclusions is difficult with such a small number of instances (especially in some cases). The computational times show a global decrease of 7.9%, which is significantly relevant compared to just using the MILP approach alone (time-consuming and with advantages only in small instances). On the other hand, GA needed 390 seconds to obtain the initial solutions. Considering everything, the warm start seems beneficial for MILP performance, optimizing computational time, and reaching optimal solutions.

In summary, given the existing planning at the institution, the different solutions produced considerable saving rates in route optimization, in addition to simplifying the planning process with faster response rates (validated by the health unit). At this stage, the benefits of all implementations and experiments are clear. These preliminary case studies and experiments are presented considering a hybrid approach and implemented in different domains, where manufacturing and HHC will be the application domains for further validation in fields with emerging needs.

5.6 General Analysis and Performance Measurement

Regardless of the experiment under study, the proposed approaches should be evaluated and validated regarding some main aspects and features, in order to analyze the influence of different instances on their performance. The comparison of different existing strategies and applications comprises a very complex task since they present some specific functionalities, purposes and other aspects that require too much effort and time to obtain the comparing measurements in terms of a general analysis. Therefore, in comparing the proposed approaches and experiments or applications, it is intended to perform a more qualitative evaluation.

In addition to that, quantitative evaluations are intended to be performed through the analysis and measurement of some behaviors of the case study system prototype. The evaluation process will consist in the assessment and quantification of the results derived from the system prototype execution in the case study scenarios, considering as main metrics the response time, output accuracy and computational resource utilization.

In this sense, this section intends to cover the different experiments and their main results, both in terms of different optimization methods, MAS and hybrid approaches. Different properties and characteristics of the experiments, either in terms of their adaptation and control of problems, or in monitoring (whether centralized or distributed), produced several insights through the use of metrics such as the response time and monitoring output accuracy. Thus, increasing the number of patients was planned, to examine the effect of more patients in the tests, as well as data variations relative to higher care frequency for the PVRP approach, increasing travel time/distance, variety of skills and longer planning horizon, are other examples that were subject to evaluation. In order to simplify the experiments, the computational resource requirements (such as processing time), can be fixed during the quantitative analysis and evaluated in a qualitative manner, considering the input information.

To monitor different system components, it is necessary to take into account the different configurations used, computational parameters, and instances, since response time and accuracy may differ depending on the problem data, complexity, and application. It will also be important to evaluate the development and/or computational effort of the different areas of knowledge where the techniques are inserted, especially, in indicators to measure the efficiency, effectiveness, and robustness of the methods used.

The performance and evaluation relatively to the optimization methods, can be done during the process of obtaining solutions, namely in the analysis of the objectives, runtime and statistical parameters to obtain information about optimization methods to support decision-making. Therefore, using this information and measuring its impact on overall system performance and how this has contributed to improving dynamic adaptation and reconfiguration of processes will be a great approach to take into account.

In terms of the models and methods of MAS, in its distributed scheduling, all the agents of the generated society can receive service requests, and answer them in the best possible manner, by trying to compose, discover, and select the most appropriate agents to offer their scheduling. Data should be compared with the initial schedule as one of the hypotheses measuring expectations about a specific feature. In case of experiments disruptions and the need of rescheduling, the collected data should be analyzed so that a decision can be made, without human intervention, on the feedback using qualitative indicators (e.g. flexibility, robustness, agility, etc.) and measuring the following quantitative KPI. Thus, some KPI can be measured, such as scheduling time, quality of composition (average quality of the scheduling composition played inside the swarm agents), agent utility (how good and agent can offer a schedule), average communication load (exchanged information in the system), average number of agents (to compose a certain schedule or task request), average forwarding messages (average cost of dispatching requests to other agents), resilience of the network (ability to remove agents from the network without incurring loss of performance), and finally, the average message size (exchange message between the agents).

As for the hybrid approaches, they produced extremely interesting results because they integrate the fast and intelligent solutions, combined with the inherent optimization of a central algorithm. However, a distributed approach is expected to require more network resources, while a centralized approach (using only MAS or just optimization methods) is expected to require more memory. In this sense, the distributed approach may be qualitatively better based on its flexibility and adaptability to self-scheduling.

In the Table 7, the set of evaluation parameters intended to be performed is summarized:

Table 7: Summary of the proposed approach evaluation and metrics.

Description	**Metric**	**Expected Results**
Evaluate solutions, runtime and statistical parameters in the optimization methods	Parameters, execution time, statistical analysis, quality, computational effort of execution and robustness	Adjust the parameters, solving the problems in a reasonable time, guarantee the quality of the "optimal" solution and apply different problems and instances
Compare, in a quantitative manner, the MAS	Scalability, interactions and flexibility (performance of all previous KPI).	Cooperating and evolve in order to reduce and increase several points (e.g. decrease the schedule costs and improves the utility).
Evaluate the monitoring and diagnosis tasks considering the hybrid approach	Optimized solutions, response time, response accuracy, responsiveness, and rescheduling autonomy	Decentralized approach with dynamic responses and support decision-making in case of disruptions

As there are different experiments, with different or combined strategy applications, it is important to have different analysis metrics, where for example, the response time is one of the main general KPI to all strategies.

Regarding the experiments with optimization methods, the Figure 45 presents part of the performance obtained by each of them in the process until the arrival of the final solution. In these implementations, different data instance values (number of patients or locations) were used, being able to relate to the number of vehicles or number of nurses. Each instance can be considered a different situation or case, and therefore it is important to explain the reasons for this:

- Data availability: if the implementation came up early in the problem research and had little data available at the beginning, it is understandable that it used a smaller number of instances. For example, it can also be useful to use different datasets to capture the widest possible range of situations relevant to the problem.

- Problem complexity: depending on the resources and the size of the dataset, different optimization methods may be more or less appropriate. Some datasets might include a larger number of patients, locations, or time constraints that affect the application, for example, exact methods, due to overfitting and computational issues (e.g., execution time). On the other hand, for a large dataset, it may be necessary to use more advanced and robust optimization methods (approximate approaches) to deal with the problem. Furthermore, different instances provide insights about how these methods behave under different complexity scenarios.

- Objectives: the study may justify the use of different values on the data instances. For example, if the idea was to test the effectiveness of different optimization methods on different sizes of datasets, different values could have been used to evaluate the performance of the methods.

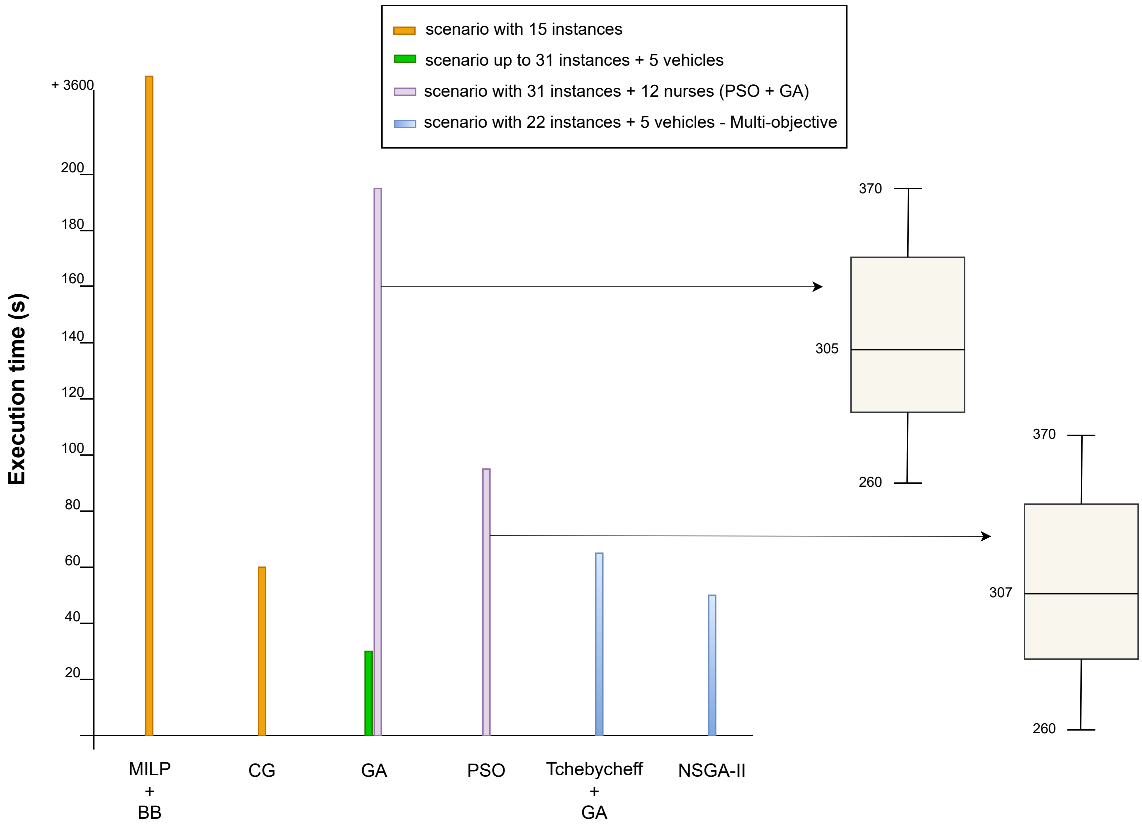

Figure 45: Comparison in terms of performance of the optimization methods.

Reporting the results of optimization methods is a challenging task with many potential pitfalls. In terms of execution time, it is possible to verify performance duality in the exact methods. When using the PVRP model with a MILP approach and the exact method BB, despite the optimal solution obtained, the computational effort is very large, since it took 11 hours. On the other hand, the CG approach, for the same scenario, allowed to decompose the problem and greatly reduce the search space, returning an optimal solution but obtained much faster. However, the CG approach revealed a much greater effort to model problems, and its robustness to be extended to higher instances will need to be studied in the future.

Moreover, the GA and PSO metaheuristics were the algorithms chosen so that, on one hand, an evolutionary type algorithm and, on the other hand, an algorithm more in a swarm context were coded to solve different instances of real problems in HHC. GA was able to solve a problem of up to 31 instances (a simple case that varied the input of data), and was able to solve the problems quickly and with fairly acceptable solutions. In turn, when subjected to a scenario with higher instances (considering the set of nurses), it already took around 3 minutes to execute a set of runs and select the best solution. PSO for the same scenario and number of instances, obtained the same solution as the GA algorithm, but in less than 2 minutes, revealing more robust and effective characteristics in running the problems. Furthermore, these two methods, which are stochastic in nature, were evaluated using box plots illustrating the minimum solutions obtained, the median and the maximum solutions found, without outliers.

Finally, there were the multi-objective approaches, which were applied using different models (one with a combination of the Tchebycheff metric plus GA and another with the NSGA-II). For the same number of instances, the NSGA-II algorithm was able to obtain the optimal solutions faster, even sought solving the most complex problem, which simultaneously minimize 3 objective functions.

This brief comparison of optimization techniques reveals that they are excellent strategies that guide the search process. The goal of efficiently exploring the search space in order to find optimal or near–optimal solutions has often been achieved and in reasonable time. Furthermore, some of the techniques range from simple local search procedures to complex learning processes and models. The computational effort is much higher in exact techniques, so by using multi-objective and metaheuristic approaches, the effort is reduced and its robustness is greater. It should also be noted that many solutions required adjustment to the intrinsic parameters of the methods (maximum of iterations, functions evaluations, % of internal procedures, among others) to guarantee the quality of the solutions in different problems and instances. Further analyzing the objectives and feasible and high quality solutions for each studied problem, it reveals that the HHC system is highly benefited by optimization methods and its impact on reducing, either costs or service times, has contributed to the improvement of the management and route planning and scheduling.

The study of a self-organized system with autonomous capabilities and reactivity allowed to generate a set of intelligent interactions and behaviors. Taking into account the experiments using MAS, Figure 46 illustrates the performance in terms of the metrics analyzed and the results obtained.

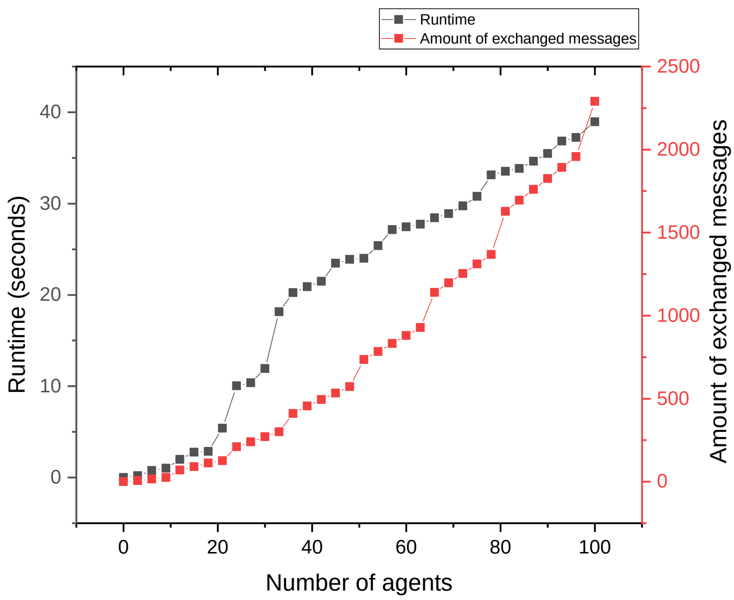

Figure 46: MAS performance.

Firstly, metrics can be defined for the agent scope, that is, measures that indicate whether the proportion of messages sent or received is too high relative to the total number of agents running. Furthermore, experiments show that MAS models, whether in simulation or real application, also exhibit an exponentially increasing coordination overhead (either in the size and/or number of messages exchanged, or in the computation required by each agent) as the number of agents in the system increases. It should also be noted that in the synchronous execution model, agents wait for messages from other agents before computing and sending out new messages themselves (personalized CNP).

The agents model allow to search for explanatory insight into the collective behavior of agents obeying simple rules, typically in natural systems, rather than in solving, for example, manufacturing and HHC problems. In general terms of the MAS experiments, all the answers and solutions given were obtained extremely quickly, even in emergency situations or in real-time interruptions. The collected data was analyzed using Figure 46, where it can be seen that the decision-making support capability, with or without minimal human intervention, never exceeded 40 seconds of runtime, for tests from creation to deployment of 100 agents.

In this sense, taking into account these metrics and the dynamic solutions obtained, the performance of the MAS models is successfully demonstrated for manufacturing, routing and scheduling problems, which achieves and maintains a high degree of scalability and robustness even in environments that are outside the range of trained scenarios (adaptation and self-organization in case of disruptions). The feedback from qualitative indicators (flexibility, agility and dynamic collaboration), positively measures the main KPI, which proves to be a resilient network (adds and removes agents easily, without loss of performance), providing solutions in situations where expertise is spatially and temporally distributed. A MAS enhances overall system performance, specifically along the dimensions of computational efficiency, reliability, extensibility, maintainability, and reusability.

Finally, strategies that use hybridization, such as parallelism, cooperation, and search space decomposition, make the decision easier for the end user as they have a wider range of solutions at their disposal. Comparative analysis shows that hybridization is not a strong feature in existing frameworks and, for that reason, it was decided to follow this research line. Figure 47 draws a general analysis of the hybrid approach and illustrates the metrics for monitoring and experimental diagnosis, taking into account the results obtained.

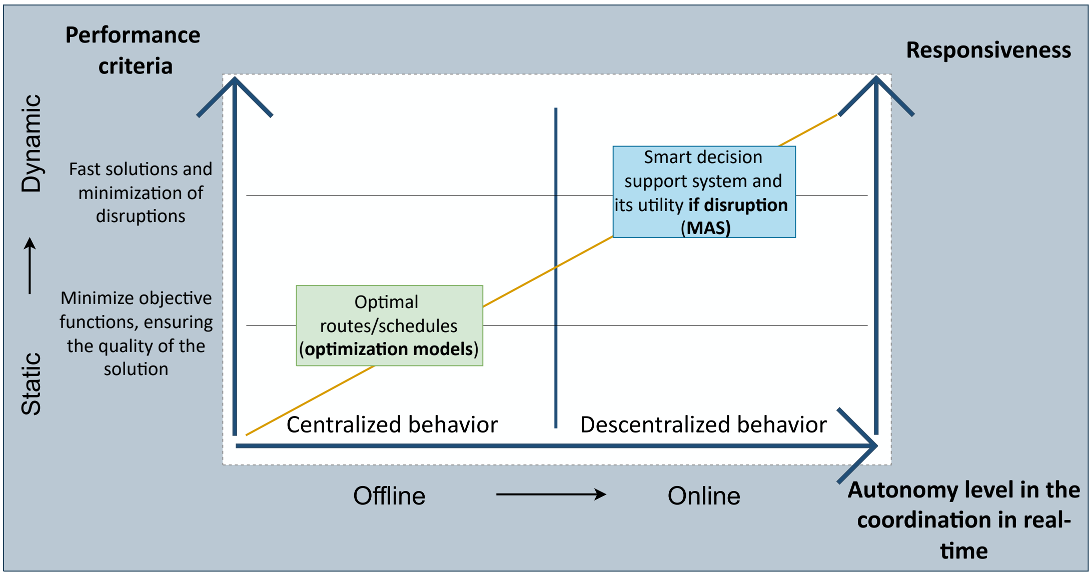

Figure 47: Performance evaluation of hybrid approaches.

The proposed hybrid design approaches combine optimization models and MAS, significantly increasing their practicality and explainability because real-world environments will likely vary outside the trained range of HHC or manufacturing scenarios. The motivation was to try to transform complex things in a simple and effective way that allows the end user to mimic nature's insights (optimization models), and to develop powerful adaptive systems (MAS) capable of evolving, thus dealing with the current challenges imposed on HHC systems.

The experimental results can achieve, on the one hand, optimized solutions from a centralized behavior (well-prepared schedules and route plans), but on the other hand, also have the ability to obtain fast and smart responses (from a decentralized behavior), even in cases of disruptions. Taking into account the level of autonomy for coordinating responses to scheduling, the dynamics of switching between offline and online modes stands out. Change, on the one hand, can happen automatically in case of an emergency or disruption in the system, where agents move from a background to a master plan to handle the situation. On the other hand, the transition between modes can be requested by the user, allowing them to choose between using an optimized approach in offline mode or a dynamic and distributed model in online mode. Thus, this flexibility to adapt to the needs of the problem is a strength of the hybrid approach. The tested applications highlight the social and environmental benefits generated, with more sustainable and efficient use of operational infrastructure resources, task effort distribution, scalability, reduced impact of broken processes and faster and more accurate reaction to condition changes. The system also has the ability to provide innovative solutions that have an impact or improve the efficiency of any problem, moving from more static to dynamic models (fast and reactive responses), and moving from centralized to decentralized behaviors that better deal with unpredictability. Additionally, this hybrid strategy has itself shown great utility in solving complex optimization processes using a decentralized approach that can generate a greater level of autonomy in problem coordination.

Taking into account the solutions of the different experiments, Table 8 summarizes the results obtained in terms of relevant criteria (KPI). The KPI considered involves the criteria of runtime (processing efficiency), solution accuracy (feasibility and quality of solutions), scalability (problem sizes and complexity), reliability more flexibility (ability to deal with changes and adaptability) and finally, sustainability plus reliability (safety and efficient and effective long term management of resources). These KPI will allow a fair comparison of different optimization methods, MAS and hybrid approach, when applied to HHCSRP, being a useful tool for evaluating the effectiveness and performance of the system being proposed. In this analysis of the KPI, a qualitative scale was used, since the numerical results have been presented before and thus are more easily accessible, makes the scale more flexible and reflects a more subjective nature of the criteria. The qualitative scale uses the standards of "bad", "good" and "optimum". These categories are intuitive since "bad" represents a performance below or in line with the minimum acceptable, "good" represents a satisfactory performance but with room for improvement, and "optimum" represents an ideal performance, which is difficult or impossible to exceed.

Table 8: Comparison of different solution approaches in terms of KPI.

		KPI				
	Solving Approach	**Runtime**	**Solution Accuracy**	**Scalability**	**Robusteness + Flexibility**	**Sustainability + Reliability**
Optimization Module	Exact Methods	bad	optimum	bad	bad	bad
	GA	good	good	good	good	good
	PSO	good	good	good	good	good
	Multi-objective Optimization	good	good	good	good	optimum
MAS Module	MAS	optimum	bad	optimum	optimum	good
Proposed Hybrid Approach	Optimization + MAS	optimum	good	optimum	optimum	optimum

For example, the nature of the KPI "scalability" can be subjective, as it may depend on the context in which it is applied, and there may be physical, financial, or other limitations. However, a solution classified as "optimum" (as is the case with MAS) may be one that can handle substantial volumes of instances without compromising quality, while a "poor" solution may be one that presents difficulties, whether in processing and formulation, even under low complexity (e.g., exact methods).

Finally, the feasibility of a hybrid strategy seems to exist, since it combines the strengths of the different modules (e.g., the ability to explore and exploit the optimization methods, combined with the flexibility and responsiveness of the agent system) allowing the system to find high-quality solutions. In addition to optimizing the constraints and specifics of the HHCSRP, it allows the system to be reactive and adaptive in situations of uncertainty and real-time emergencies.

5.7 Summary

This chapter focused on different implementations throughout the research, testing, and collecting results with different implementation approaches. Multiple test instances were built to evaluate the performance of the methods/algorithms when compared to each other. Most of the experiments were tested with data (or subsets) from the Santa Maria Health Unit. Due to the dynamics and resources of the system in question, performance measures and metrics to be taken into account when evaluating the experimental results were also mentioned. Furthermore, this chapter points out and discusses important contributions, most of them with indexed publications, highlighting the benefits of using optimization methods, MAS or hybrid approaches that combine the first two strategies. These experiments allowed the validation of the architecture, namely in terms of the integrated core modules, and its applicability to credible multidisciplinary entities, such as IPSS, which have similar problems and needs, but different contexts. The contribution of this chapter proves that the proposed approach increases the reliability and quality of the scheduling solution, and increases support for group decision-making.

On the basis of that, the experimental validations produced positive insights in an attempt to leverage and prototype a distributed scheduling and routing system, which will be presented in the following chapter.

6

Prototype – DOCtoR

"Technology is nothing. What's important is that you have faith in people, that they're basically good and smart — and if you give them tools, they'll do wonderful things with them. Tools are just tools. They either work, or they don't work." - Steve Jobs.

In the previous chapters, an intelligent and distributed scheduling architecture was described based on the optimization methods and MAS paradigm. The objective was to address many implementations to evaluate optimized solutions or agile reactions to unexpected events at the real-time level. Thus, the creation and validation of a prototype (web/app system) is required to verify the correctness and the applicability of its concepts.

The prototype, called DOCtoR, requires the application of the architecture concepts (as a *mHealth*) in a real case study and a further analysis of the scheduling control system, management data, and monitoring behavior under several different routing/allocation scenarios. The implementation of the system concepts in a prototype will be described, focusing mainly on the development platform (external services, algorithms, models, languages, and tools) and the integration of all modules. DOCtoR will be based on the digitalization of the home visiting service operational process and the collaboration of intelligent and optimization tools for the planning and response strategy. A real case will also be used to test the concepts of the system by defining the HHC service and its multiple scenarios. Finally, the experimental results will be analyzed and some conclusions about the validation of the prototype will be discussed.

It is important to note that the system to be presented in this chapter, is an extension of the thesis, since it does not contribute to answering any of the research questions. However, it is a prototype application that allows the user to interact with the specified system, implemented in a real environment.

6.1 Real Case Study

The real case study had the active participation of OSPM, an IPSS in the district of Bragança, Portugal [144]. Despite being a region with low population density, Bragança is characterized by an increasing number of elderly people dependent on social support or health services [74]. There are several support institutions in the municipality and district of Bragança, where OSPM stands out. Furthermore, this institution is one of the oldest, has the largest number of effective and/or temporary/volunteer workers [43]. Besides its status in the region and its economic and social weight, the collaboration of this institution was very important in this work.

OSPM began with social action activities and became an association in 1993. In 2000, it created a reception center in the same city, which would allow the development of a regular activity of family support, rehabilitation and social insertion of the needy. More recently, in 2009, and taking into account the growing needs of the Bragança district, facilities were inaugurated where most of the services are concentrated: residential center, social center, nursery HHC or just home care, medical services, day center, physiotherapy, among many others. The entity thus focuses on various social responses, whose mission is to support the elderly population, children, rehabilitation, the community, and social inclusion in the region. One of its greatest strengths is its home support service, which also has the largest number of users and applicants [43].

The home support service is a social response that consists of providing personalized and individualized services or care at home to individuals (generally 60 or older, who due to illness, or disability, cannot temporarily or permanently ensure the satisfaction of basic needs and/or activities of daily living). The objective is to contribute to the improvement of the quality of life of the user/client and family, as well as to perpetuate their stay at home, thus delaying their institutionalization [144].

Given the above, a set of information was collected in an attempt to place the institution in the context of the local social economy and to understand its process of managing the home visiting service. OSPM, according to the data collected and also present in the social chart of the municipality of Bragança, has the capacity and provides this service to about 90 users (a total of 86 patients are currently present), which turns out to be a large percentage of its social response. In addition, OSPM shared data on the characterization of the information, namely the services offered and provided by the entity, patient data, and certain assumptions and constraints that are considered for the allocations, planning and routes of visits.

Regarding the services provided, these may vary and be related to:

- Supply of meals (every day, including weekends and holidays);
- Personal Hygiene Care;
- Housing Hygiene (restricted to spaces used by the user);
- Treatment of clothing for personal use by the user/client;
- Performing occupational activities;
- Psychosocial Support;
- Medical care, nursing, particularly when the user/client has no family support.

For the satisfaction of the services, the provision of care at home is composed of the areas of the kitchen, laundry and reception and administrative services. An average duration time is assigned to each type of service (estimated by OSPM), which, for example, in the food delivery service is counted as 5 minutes, approximately 30 minutes for personal hygiene, 10 minutes for laundry and 45 minutes for house cleaning. These data should then be considered for route planning.

Each registered patient provides the following information: name, address, gender, birth date, care worker gender preference, treatment priority and services required. For privacy reasons, the data are represented as graphs in Figure 48, avoiding the exposure of names, dates, and/or places of residence.

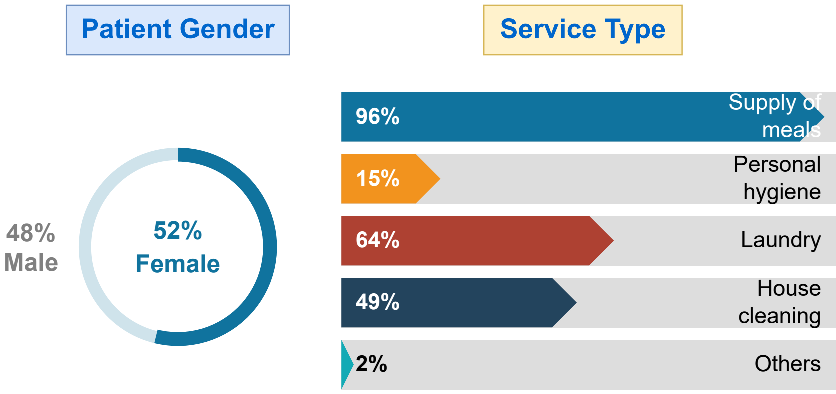

Figure 48: OSPM data caracterization.

Analyzing the patients gender, the graph allows to verify that 52% of the patients are female and 48% are male. Regarding the service type, it is possible to see that most patients request and need a meal supply (lunch shift). It should be noted that the different types of service are carried out from Monday to Friday (1 to 5 times), Saturdays, or Sundays. In addition, there are several patients who require more than one type of service, on the same day or on different days. The updated schedule for this service starts at 8:30 am and ends at 5:30 pm, 7 days a week. Sometimes, there are patients who require time windows in the delivery of some type of service (e.g., patient A needs his personal hygiene to be performed after waking up, that is, in the morning). Only 3% of the patients indicated gender preference for the home care technician who will care for them. In all these exceptions, both male and female patients have requested female care workers. Although the percentage is small, these are extremely important indications in order to respect the patient's wishes and take this requirement into account when planning the route. Regarding the patients, 86 visiting locations were counted and a distance matrix was automatically constructed between each of the points. The locations belonged mostly to the municipality of Bragança, which covers about $1000km^2$.

In addition to the above mentioned data, OSPM has 7 vehicles totally dedicated to home support and with the effective participation of 4 employees (care workers or technicians) plus the home service director (manager and operational planner).

Once this information was collected, an attempt was made to understand the daily operation, from management planning to the execution of the home support service in the field. The organizational, structural and operational management takes into account the aspects of the Figure 49. OSPM has an interdependent relationship with its surrounding environment, because it obtains from this environment the resources (inputs) necessary for its operation and it is in this environment that it places its results (outputs).

Its management process, and in particular with regard to the home visit service, involves a dynamic and continuous procedure towards quality and meeting the needs of patients/users. However, nowadays, several difficulties arise in the 4 fundamental functions: in planning, organizing, managing and evaluating. With the Covid-19 pandemic, the volume of patient needs increased exponentially. It was necessary to recognize that the current manual planning and organizational strategy demanded an additional effort in addition to the service costs incurred. The 4 primary functions of OSPM are still performed manually (in a centralized manner), on paper or using excel sheets, which often leads to sloppy information, inefficient scheduling/routing solutions, with no viable replacement, and employee fatigue. In turn, non-optimized and time- or task-consuming solutions entail aspects of wrong visit time

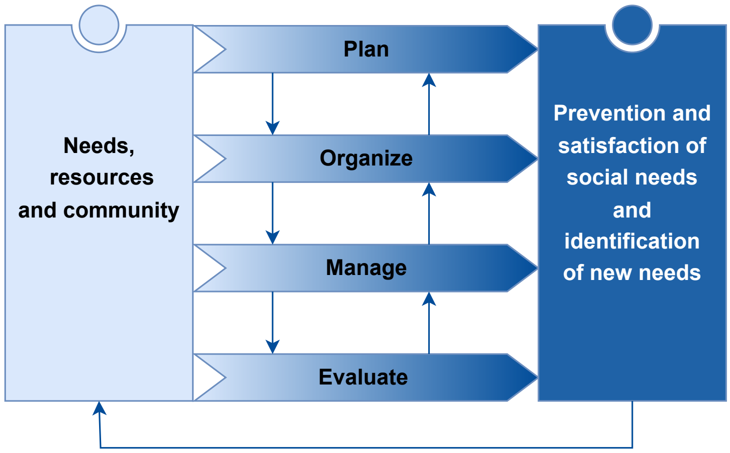

Figure 49: Overview of the management process in OSPM - home care service.

estimations, poorly planned, bad allocated routes, and with possible effects on the satisfaction of both the care workers and the patients themselves. In addition, it is difficult to manage and reorganize unexpected events or real-time emergencies (e.g., broken down vehicle requesting replacement, fall of a patient who needs immediate help or emergency medication delivery).

The management realized the need to implement digital means and optimized strategies (facilitate access and handling of information), as they could improve the evaluation, the monitoring function and achieve the desired efficiency and quality in home action. The IPSS has a relatively low experience in digital literacy, so this chapter sought generating mechanisms for route optimization and scheduling, allowing these to be the smart answer to improve current solutions, costs, and income, ensuring daily sustainability and preventively managing possible failures or unforeseen events, or even expanding the service. In addition, a digitalized tool will be an innovative and necessary means for daily management (whether by the manager or care workers) and will provide greater data distribution, flexibility and balance to link strategic planning to the operational control of home visits.

6.2 Methodology and Supporting Software

For the design, development and creation of DOCtoR, project management methodologies were taken into account from the beginning, such as an agile development, more specifically Scrum and the Kanban strategy. Basically, Agile is a structured and iterative approach to project management and product development. Kanban can be applied to visualize tasks, limit work in progress, and maximize efficiency (or flow), regardless of the methodology being used to get the work done.Scrum is an iterative incremental work method that provides a highly prescriptive way to complete the work. Its use commits to completing an increment of work, which is potentially shippable, through defined intervals called sprints. It is intended to create learning cycles to quickly collect and integrate customer feedback. In the development of DOCtoR, processes, roles, ceremonies, and artifacts were not inserted, as they are in the business or industrial world. Figure 50 illustrates the agile approach to managing the DOCtoR system, so that all information is recorded from the initial steps, small increments of work, to continuous improvements and flexible processes from what is “being done” to “done”.

This methodology was also important to generate positive insights into the technological work being developed, quality tests, and deployment with real data. In addition, with this constant feedback throughout the sprints (it was

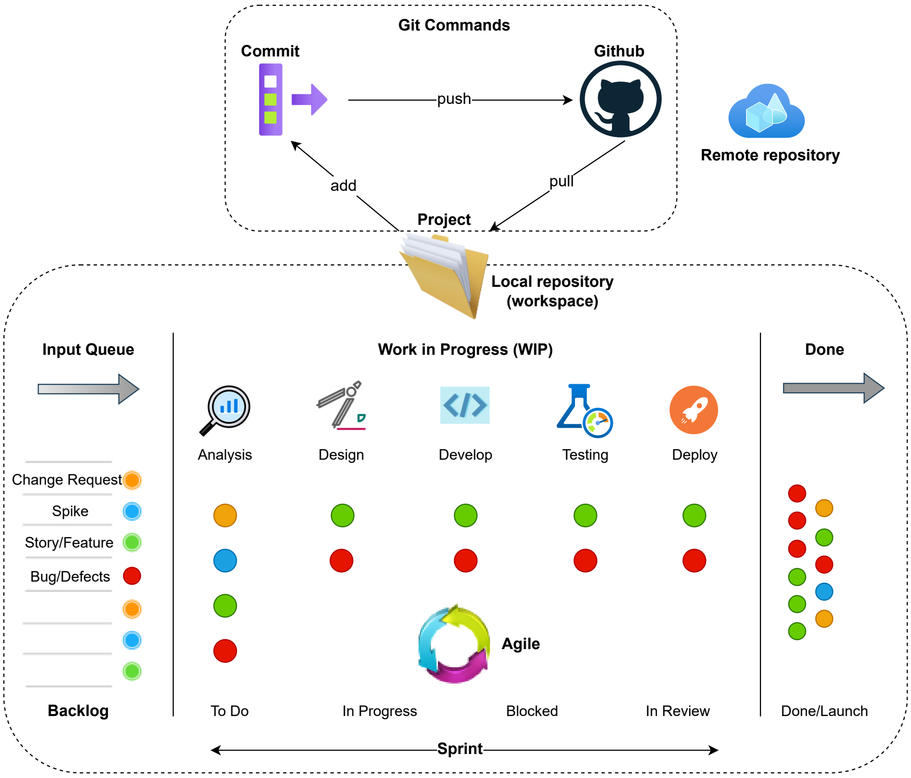

Figure 50: Project management methodology applied to the DOCtoR prototype.

adopted for 2 weeks), reviews were carried out that allowed prioritizing and assigning sizes to new inputs, cards or features in the backlog, which can be blocked or removed based on prioritization. The advantage of this mixture of methodologies in the management of DOCtoR allowed not to have high control over what is in scope, but let us go with the flow.

This process helps a team (in this case, in particular, the doctoral student), in the organization and distribution of the tasks, and allows a more efficient and balanced improvement and resolution of problems with the supervisors and the "client" (OSPM). For flexible project management, the Trello platform was used. The project emerged as a solution to the IPSS problem, however, the architecture was challenging to adapt to other institutions and their business model.

In addition, the Git tool was also adopted, on Git workflow recommendation. This well-supported open source tool is flexible enough to support a range of workflows that suit the needs of any given software [37]. Git key functions support and enhance agile development, that is, changes can be pushed quickly through the deployment pipeline. Thus, in DOCtoR development Git was used as the version control system (software) and GitHub as the source code hosting service. Git is a version control system that allows you to track changes in computer files and coordinate the work on those files among multiple people. Mostly the development was carried out in a local repository (personal machine) however it was possible to make a local copy and copy it to a GitHub account (remote repository), namely through Git functions such as commit, push, pull and sync. Committing is the process that records changes in the repository, kind of like a snapshot of the current status, which by default are made locally. Pushing sends the recent commit history from the local repository to the remote repository. If only one person is working on a repository, pushing is fairly simple. If others are accessing the repository, you may need to pull before you can push. A pull grabs any changes from the GitHub repository and merges them into your local repository. Syncing is like pulling, but instead of connecting to your GitHub copy, it goes back to the original repository and brings in any changes. Once you've synced your repository, you need to push those changes back to your GitHub account. With all these functions, Git allows you to have branching capabilities. Unlike centralized version control systems, Git branches are cheap and easy to merge. This facilitates the feature branch workflow popular with many Git users. Feature branches provide an isolated environment for every change to your codebase, performance (reliably), security, quality, and wide acceptance of the community.

In addition, the proposed system integrates some supporting software, such as cloud tools, Google OR-Tools, microservices such as Google Maps API and Distance Matrix, and optimization algorithms.

Google OR-Tools is an open source solver tool that was adopted to manage a set of algorithms already available in the cloud and thus deal with well-known VRP problems, similar to our real scenario. Google OR-Tools [161], has recently been launched (2019) by Google researchers and programmers, offering many libraries and different solutions for different versions of issues and/or forms of routing, packing, assignment, and scheduling. It features a cloud system with several learning libraries, statistical data, VRP, a programming environment, flexibility, and functionality that is simple to use across various programming languages (such as Python, Java or C#). This tool also comes with certain predefined algorithms, including (meta-)heuristics and a number of procedures, mechanisms and methods for specifying goals, variables, constraints, and/or parameters.

In order to solve challenging combinatorial optimization problems, Google OR-Tools is a quick and portable package that allows for tests and/or applications to real-world issues [182, 181, 20]. Furthermore, substantial online documentation on OR-Tools, packed with examples and libraries, demonstrates the huge potential of the platform in the area of OR systems. Additionally, the integration of skills with external systems or online services is allowed, including visualization systems and the Google Maps API, distance matrix API, and others.

The Google Maps Platform is a set of APIs and SDKs[1] that allow developers to embed Google Maps into mobile apps and web pages or retrieve data from Google Maps. The use of this functionality allows the creation of apps with Google information about the real world, creating realistic experiences in real time with the latest features of Maps, Routes and Places of the Google Maps Platform. In addition, markers, reactive events, information windows, among other libraries or features can be added. Maps can be dynamic, interactive, personalized, or static, depending on the website or application. In addition, routes can be provided for various means of transport, with real-time traffic information (which is a great advantage for DOCtoR). The travel times and distances to various origins and destinations will be calculated using the Distance Matrix.

On the other hand, the distance matrix API provides travel distance and time for a matrix of origins and destinations and consists of rows containing duration and distance values for each pair. Distance Matrix is available in several forms: as a standalone API or as part of the client-side Maps JavaScript API. By default, the distance matrix API returns information based on the recommended route between the start and end points. The user can request distance data for different modes of transport, request distance data in different units such as kilometers or miles, and estimate the travel time in transit. Another important factor is that this API uses the pay-per-use model, where each request generates calls and depending on the type of request (usually the most basic) it does not generate costs at this time.

In addition, cloud-based technologies, such as Azure, were implemented to minimize workloads and optimize the scalability and cost of the solution. Furthermore, cloud computing allows to construct value propositions showing

[1] SDK is a development kit that facilitates the use of an API.

increased efficiencies and reduced lifetime costs. Azure is a Microsoft-owned cloud computing platform that provides access, management, and development of applications and services through data centers distributed throughout the world. For that, it also supports many different programming languages, tools and frameworks, including Microsoft and third-party specific software and systems. Additionally, Azure takes advantage of pay-as-you-go to get free services, without commitments, and with cancelation at any time. However, the solution is completely agnostic to any cloud server.

6.3 DOCtoR System Overview

The DOCtoR prototype presents a solution to optimize the manual process of planning and managing routes in the HHC or social care areas. In this sense, the platform combines a set of optimization approaches and smart skills to efficiently manage the home care service, as well as digitalize the operational planning of visits, in order to empower organizations, as well as improve both business and patient satisfaction.

Therefore, it is expected that through the tool DOCtoR it will be possible to obtain an efficient and optimized scheduling and routing for different home care tasks and settings and to benefit from intelligent management of its operational service, reducing significant planning effort and controlling delays or unexpected events. DOCtoR platform helps with:

- Proactive scheduling and routing. Smart allocation of care worker scheduling with real-time access and traffic updates (on-the-go mobile app), route optimization and instant reshuffling of a schedule to increase patient and care worker satisfaction.

- Adaptive capacity forecasting. Determine the expected workload by geography, time, and work type to provide the clearest and most accurate picture of upcoming patient demands.

- Right person, right skill. Ensure that the home care worker has the required skill set to perform care and allows for consistent matching of caregivers with patients to improve continuity of care.

Figure 51 depicts the DOCtoR architecture, which is based on two main components: 1) a web application where the head of the OSPM plan and manages all the processes of the home visit routing and scheduling; 2) a mobile application where the care workers (or technicians) team on the road can access information about their assigned routes and patients.

The process begins with the head of the IPSS, main admin. In the web application, he/she can manage all the data and processes of route allocation and planning. In addition, the main admin will be able to add, edit or delete data, as well as dynamically visualize the route and sequence of visits on the map afterward. Finally, he/she will also be able to manage preferred aspects of both patients, care workers, or the manager himself.

On the other hand, the mobile application is designed especially for the care workers team who perform home visits. The specific data of each route assigned to each care worker can be monitored and from there a follow-up of visits to patients homes can be carried out. It should be noted that both the mobile and the web applications are accessed through a custom identification and password, which, for example, in the web application users may have different roles and, at the same time, different page views and/or permissions.

By improving scheduling management, the user can possibly respond to more patients, protect margins, and have better insights into cost structure to enable more accurate bidding on requests for proposals.

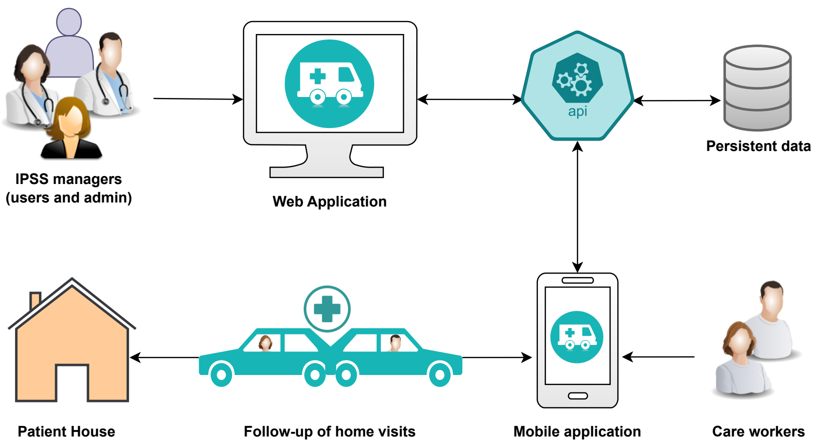

Figure 51: DOCtoR overview architecture.

6.3.1 DOCtoR Specification

The prototype DOCtoR comprises a web and a mobile application, developed in Angular and React Native, respectively. The general system can communicate with an API developed in C#. The API manages all the logic and business plan of the DOCtoR system. Figure 52 depicts the proposed DOCtoR architecture for the solution presented in the previous section.

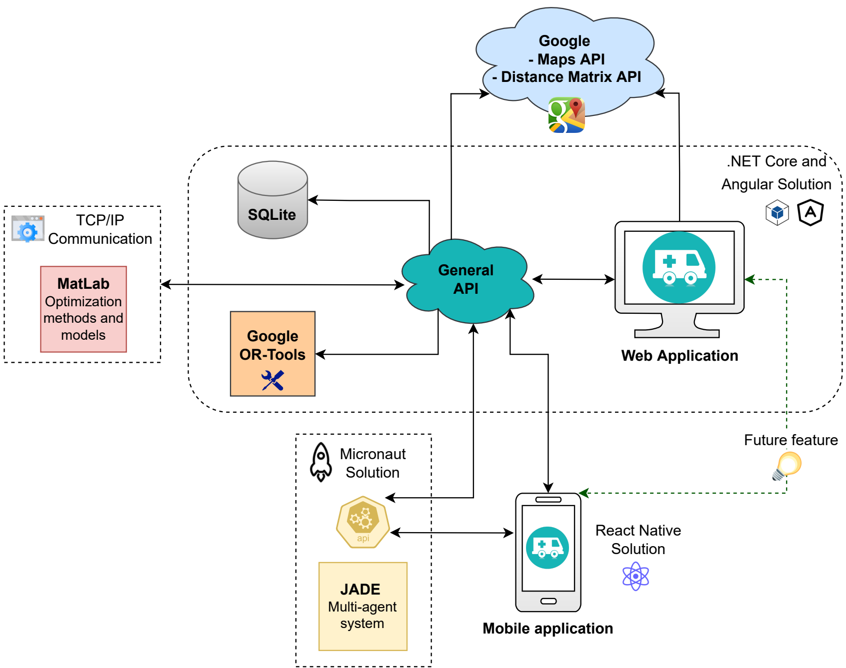

Figure 52: DOCtoR architecture specification.

The connection between each integrated module or external service can be unidirectional or bidirectional. In turn, the general API is the command center for all operations. Furthermore, it is important to point out that the database module (SQLite) stores and manages data in the form of objects or records, in a relational way, as can be seen in more detail in the Appendix C. Furthermore, in the same appendix, some of the technologies and services used to specify and contribute to the DOCtoR infrastructure can be found.

The process flow starts in the web application, which after a validated login, the head of the home care service can manage the database and create a new route. The Web application sends to API the origin location, patients ID, assigned vehicle, choose an optimization method (with some algorithm parameters) or external service (call Google OR-Tools), activate MAS (taking into account the agents involved, vehicles and patients), label and date of the visit. Thus, the MatLab software had the core task of generating optimized solutions through pre-defined models and methods (adapted from the GA, PSO, and NSGA-II algorithms), and MAS was started on the JADE platform due to the need for fast and distributed solutions or coordination of responses to unexpected events.

Then, in the API, information about maps and distance matrix is generated based on the patients selected for a visit. With the distance matrix built, the next step is to execute the solution(s) approach, which returns the optimal route based on the distance matrix, care workers and the number of assigned vehicles. The output of the solution approach and all data involving the route, allocation and scheduling are stored in the database. To allow the team of care workers to access their routes, the mobile application sends a POST request to API with the following parameters: care worker ID and route date. The returned data displayed in the mobile app is the route and its waypoints, information about the patients and required services. It should be noted that after logging in the mobile application, only the respective data and routes of the care worker to whom access has been granted will be displayed.

Regarding the methodology to represent the implementation of the DOCtoR prototype, the pseudocode of Algorithm 3 is presented, which demonstrates how the system follows an algorithm (a sequence of activities), to improve the readability of the system.

In the DOCtoR solution, the distance matrix is dynamic. Whenever the *Calculate Route* function is requested, a new matrix is built based on the patients selected for that route. To build the matrix, the Google Distance Matrix API is used.

The developed algorithm and strategy were implemented giving the user the option to choose whether to use the OR-Tools cloud service, the optimization module or the MAS module. Each module exhibits different strengths and/or disadvantages, namely in terms of speed (e.g., OR-Tools), efficiency (e.g., optimization module) and responsiveness in emergency situations (e.g., MAS module). Thus, it is possible to verify that practically all the strategies of the Chapter 5 will be linked to DOCtoR.

The API at the decision maker's command will be able to communicate and connect with MatLab (optimization module) and have at its disposal a set of optimized methods for effective solutions through metaheuristics and MOO, capable of solving very complex problems characterized by excessively large search spaces. The MatLab software, in turn, presents computer schemes that favor the implementation of this techniques, including different aspects and mathematical operators, hence its use via communication protocol. On the other hand, there is still the possibility for general API to communicate with the module MAS implemented on the JADE platform. This module enables efficient and effective management of complex distribution networks through a custom agent model for HHC. Agents are born (run in the background) as soon as a route request (by the user) is made and represent the entities involved (namely, patients and care workers). The agents can communicate with each other based on their intelligence (algorithm defined) using standard language such as ACL applied to a previously validated custom CNP. By itself, the decision maker can request the sending of quick allocations to the routes based on the requirements and parameters of the scenario. In any case, this module has the cability, even if the user does not interact with it, to be used for monitoring and suggestion after an unexpected event in real-time (e.g., emergency of a new patient or a disrupted vehicle), by rescheduling with minimal human intervention.

Algorithm 3 DOCtoR procedure

Input: *patients*, *IPSS* (Geolocation of OSPM), *vehicles*, *care_workers*
Output: Set of solution waypoints in Google Maps, task allocation and scheduling

```
num_locations ← patients.Length + 1                                  ▷ Number of patients in OSPM
distanceMatrix ← []
for x ← 0 to num_locations do
    Request to Google Distance Matrix API with x as the origin and the remaining index as destinations
    Update distanceMatrix                                        ▷ add row to the distance/time matrix
end for
Sending data to the solution approach modules
if option == "Optimization Module - MatLab" then
    sendDataForOptimization(IPSS, patients, distanceMatrix, vehicles, care_workers)
else if option == "Agents Module - JADE" then
    sendDataForAgents(IPSS, patients, distanceMatrix, vehicles, care_workers)
else
    sendDataForORTools(IPSS, patients, distanceMatrix, vehicles, care_workers);
end if

function sendDataForOptimization(IPSS, patients, distanceMatrix, vehicles, care_workers)
    Perform optimization with metaheuristics, with user choice (GA and/or PSO and/or NSGA-II)
    Return Optimized solution - TCP/IP
end function

function sendDataForAgents(IPSS, patients, distanceMatrix, vehicles, care_workers)
    Perform real-time distributed scheduling and monitoring with agent-based model
    Return distributed solution - HTTP
end function

function sendDataForORTools(IPSS, patients, distanceMatrix, vehicles, care_workers)
    Perform cloud solution for scheduling routing
    Return cloud solution
end function
```

Finally, the OR-Tools module was included in DOCtoR, which can be used as a standard solution if the user does not make any choice or when a quick and "minimally" optimized solution is required. OR-Tools was integrated (as an external service) into the architecture specification, due to its portable advantages and can be used to solve both simple and complex combinatorial optimization problems [161]. Furthermore, there are numerous examples and API documentation in the OR-Tools documentation. In DOCtoR, this module has the advantage of being the tool itself for choosing the method for solving the problem ("automatic" mode).

In general, all these suitable approaches allow solving the HHCSRP, by presenting statistical data, programming environment, flexibility, functionality, and ease of use in different programming languages and software. Moreover, these strategies combined in a digitalized architecture, monitored by cyber-physical components, make it possible to apply the approaches in a hybrid mode.

6.3.2 Web Application

Figure 53 presents the structure of the web application and some of its main features, especially the ability to digitalize, plan, and manage the calculation of routes and optimization processes of home visits in the OSPM.

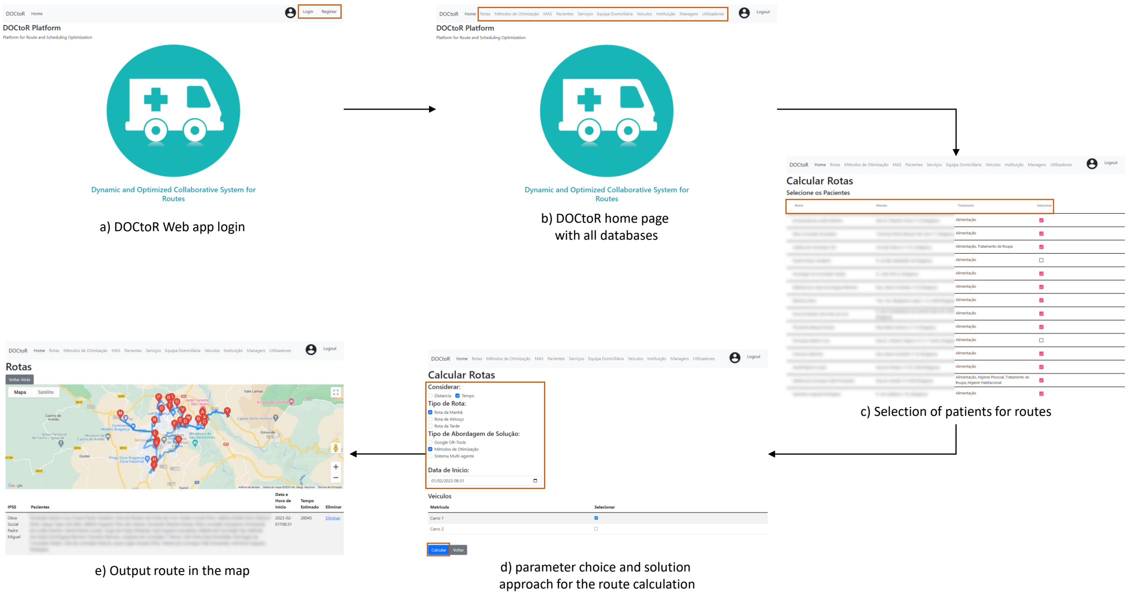

Figure 53: Web application and main functions.

After entering the web application, a print screen is displayed (a) with the DOCtoR logo, with the possibility for the user to register or log in (mostly done by the service manager). After logging in, the user is redirected to the home page (b) and is now provided with a navigation bar with database connection (add, edit, or delete data related to patients, vehicles, care workers, among others), optimization module, MAS and route planning. Since the main purpose of the web app is to allow the manager to manage and plan routes, this feature has as its first step the printout displayed on screen c), where the admin should select the patients to be included in the route (for specific day and shift). On the next screen, d), the route planning parameters must be indicated. The parameters for choosing the solution approach, shift label, date of the visit and the vehicles that will make the appointment must be transmitted. The home care team is assigned automatically to the visit via the chosen vehicle, however, it may be modified later. In screen e) is displayed the outputted route information: name of patients to visit (assignment per optimized order), estimated date and time to visit all patients and return to the depot. To generate a new route, the admin should select the “Add Route” option.

In general, the web app allows to access the following features:

1. Add information from the care worker team to the system;

2. Add patients personal information: name, address, gender, and birth date. For route calculation, the operational gender preference of the patient, the priority of treatment, and the service provided are also considered. In addition, time windows can be added for patients to receive services;

3. Add the vehicles and assign the team to them;

4. Add types of care service, including the description of the service and the estimated time it takes. The service time is essential to be registered to determine more accurate times for the route planning and the assignment of the care worker teams;

5. Planning routes. The main admin must select a set of patients (for the daily work service), the parameter (objective) that should be considered for the calculation (multi-criteria for time and distance objective), the date of the visit, and the assigned vehicle.

6.3.3 Mobile Application

The main purpose of the mobile application is to facilitate quick and easy access to optimized routes and schedules for each care worker, and in addition: faster operation (sometimes faster than websites), personalized experience, online and offline capabilities, increased efficiency, the possibility of monitoring, instant updates and notification, affordability, and enhanced user interaction. An account is assigned to each member of the care worker team to authenticate in the mobile and web applications.

Figure 54 illustrates the design and user flow that helps to understand how care workers can use the app.

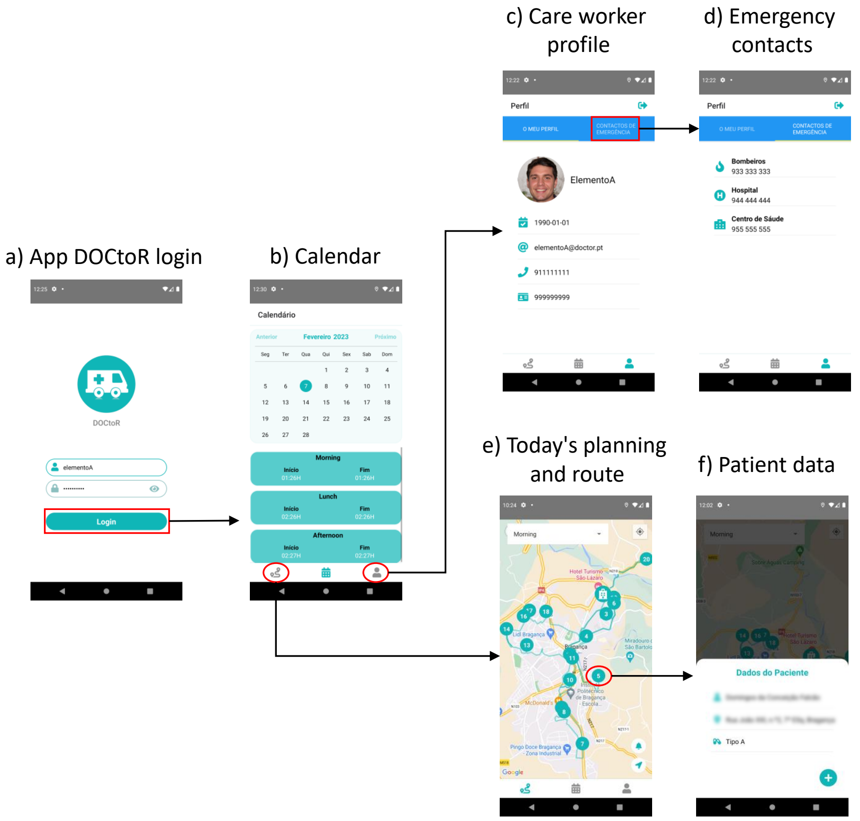

Figure 54: Mobile application and main functionalities.

Once care workers log in to the mobile application (a), they are redirected to screen b), as can be seen in Figure 54, where the calendar shows the routes assigned for that current day (or they can search for other days). In this screen, the care worker can check the plans that have been assigned to him/her for a selected day. Under the calendar, the shift options for the day, a maximum of 3, can be checked as mentioned before. Selecting a label allows to automatically show that route on the map as shown in screen e). The screen b), in the bottom bar, has two more options: c) care worker profile and e) related to route map and patient assignments.

Pressing the care worker profile option button, screen c), the care worker can see personal information and emergency contacts (d). On the other hand, by pressing the route button, the user is redirected to the planning and route screen (e), corresponding to the current day. This screen presents optimized routes for the day, notifications, and the option to open the route in *Navigation Mode* of the Google Maps application. The OSPM symbol is marked as a building icon, and patients are marked with a number that identifies the visit in the route sequence, depending on the number of patients to visit in that route. For each day a care worker can be assigned a maximum of 3 different routes referring to morning, lunch and afternoon shifts. The care worker can change the route in the check box at the top of the screen. Pressing one of the patients icons gives access to the screen f), where important information about the patient is displayed, such as name, address and treatment to perform.

In general, the main functionalities present in the application are:

1. The map the routes assigned and its sequence for the day, which are labeled as: Morning, Lunch or Afternoon. It also presents important information about the patients included in the route;

2. Notifications about the patients (remarks left by the web application);

3. Register a patient as visited and have the option to leave an observation about him (note for a next visit);

4. The calendar with the routes assigned for each day of each shift. These routes can also be seen on the map;

5. Personal information and emergency contacts.

6.4 Results and Validation

This section presents the evaluation and validation of the first version of the DOCtoR web/app prototype. A case study is presented to better understand the system process, main features and functionalities. In addition, the quantitative evaluations are intended to be performed by analyzing and measuring some behaviors of the case study system prototype. The evaluation process will consist of assessing and quantifying the results derived from the DOCtoR execution in real scenarios, considering response time, output accuracy, solution optimization (comparison with the current ones) and use of computational resources as main metrics.

To guarantee that the results obtained in subsequent experiments are trustworthy and of high quality, it is crucial to validate the solutions that have been created. It will be possible to validate the solutions through, for example, two ways: review by the care worker or manager (evaluate the routes that have been produced after solving the routing problem to determine whether or not they are valid and usable in terms of decision making); ensure that the minimum times are guaranteed (route working time lower bound).

6.4.1 Case Study Application

In this scenario, the service director has calculated a morning shift that passes through 24 patients (23 pre-defined in advance and a new patient would be inserted in an unexpected event where the routes take place), assigning the *Care Worker 1* and *Care Worker 2*, using two vehicles, for these routes. On the day of the visit, the care workers log into their accounts on the mobile app to check their appointments for the day.

Figure 55 presents an example of the mobile care worker application. As can be seen in the representation, on the Map Screen, the route was displayed for the morning shift of a specific day, with the identification of the patients to be visited.

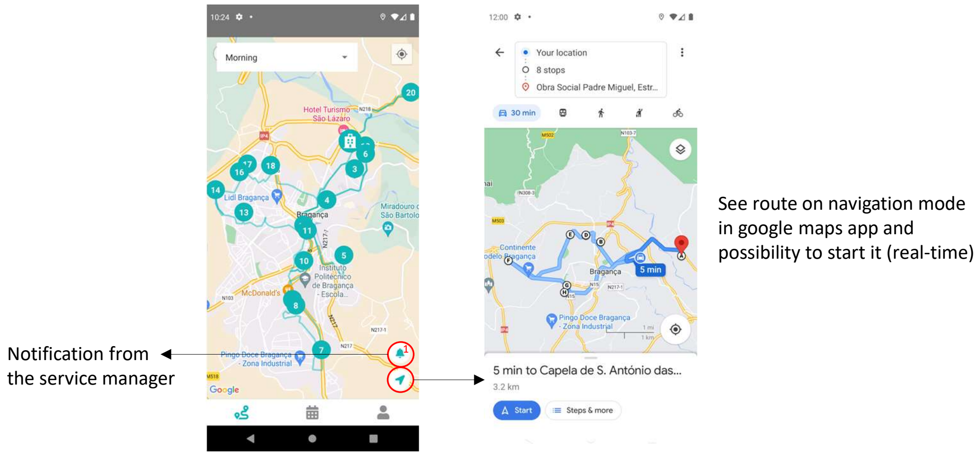

Figure 55: Case study using mobile app.

Clicking on each patient icon allows the care worker to access personal information (as seen before) that may be important for the work to be performed. To begin the shift the care worker team should press the navigation button to enter the navigation mode in the Google Maps app, and start the route if applicable.

Furthermore, assuming that all operational planning is carried out for the most part without unexpected events or emergency situations, DOCtoR has intelligent functionality for editing or recalculating the route in real-time. To this end, when an emergent patient appears requesting some type of service (unexpected lunch delivery), or when there is a breakdown of a vehicle that cannot complete its route, MAS will be able to autonomously adjust and suggest dynamic changes to the current routes, taking into account different dynamic alternatives (as seen in the previous chapter). In addition, they can also check if any notification has been received from OSPM, which in this case received an alert as shown in Figure 55. In the scenario, the service manager, after the routes started, entered a new patient in the API and gave priority to receiving a lunch delivery on that same shift that the current ones took place. Thus, whenever an unexpected event happens, such as new information from a patient, MAS has replication mechanisms for all the agents involved and others that appear at runtime (e.g., new patient, new vehicle, new care worker). In this way, the connection API via JADE is activated again, the agent model receives the new information and has the ability to react autonomously, applying a new protocol to readjust the new need, in this case allocating a new patient to one of the available routes. Finally, JADE adapts the exchange of messages between agents to obtain a solution by communicating it with the mobile app in terms of notification/alert. In this specific case, MAS strategy was to add the new patient at the end of the *Care Worker 1* route, because it would probably be the route that would end with the most optimized time after its addition. However, it should be noted that this functionality excludes human intervention, avoiding phone calls, readjustments through messages, among others, and suggests an optimized solution with the data at hand, but it is always up to the decision maker (care worker and manager) to accept or not.

In addition, the Web app is able to filter and generate a patient visit control spreadsheet for each care worker on the home care team. Figure 56 illustrates, as an example, a schedule and map of services for *Care Worker 1* on the day of the case study application.

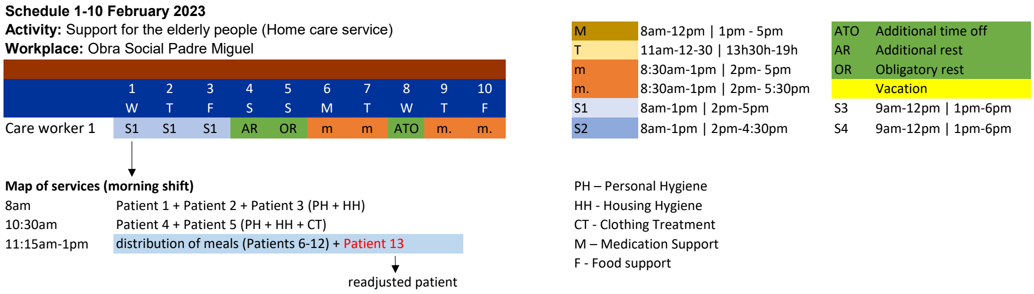

Figure 56: Schedule and service map (home care visits).

With this practical spreadsheet generated in the web application dashboard, the manager will be able to administer and control the service maps of each care worker in a single place, sending them by email/phone. Moreover, it is faster to build daily, weekly or monthly reports, with centralized information and dynamically collected data.

With this simple case study application, the OSPM manager, instead of continuing to manually create staff schedules and routes using Excel sheets, which was time-consuming and inefficient, can consider adapting DOCtoR to their home service. Once they implemented a workforce management solution, they can improve their scheduling procedures by accurately balancing their shifts. They were also able to identify demand patterns and avoid under- and overstaffing their schedules and routes.

6.4.2 DOCtoR Performance

This section presents the results associated with the evaluation of each solution approach in DOCtoR. To evaluate average time performance of the solution approach, some route scenarios were executed with variations in the instance of the number of patients for each visit in order to gradually increase the complexity. The times collected refer to the process of creating a route, from the moment it receives the data via *POST* request until it saves the solution output in the database. The tests were performed on a Huawei machine with an x64 bits system, 16 GB RAM and Intel(R) Core(TM) i7-10510U CPU.

In order to simplify the testbed, the computational resource requirements (such as runtime performance), can be generated during the quantitative analysis and evaluated in a qualitative manner, considering the input information, variables and constraints. Thus, Figure 57 presents the runtime performance (until the solution is obtained and transmitted to the apps) versus the number of patients (instances and associated data) that are defined as the default value for various scenarios.

The runtime was calculated for each integrated solution approach module. The time performance scale, as expected, is proportional to the number of patients on the route and their location. However, it is possible to verify that the fastest solution approach was the Google OR-Tools module (external service). Although this tool did not count for the research experiments in the previous chapter, it was decided to include it due to its innovative aspect of cloud computing with ease of integration into the proposed system. Anyway, it is necessary to explain why the external service performed better, in terms of runtime, than the optimization and MAS module implemented in the DOCtoR proving to be a more suitable solution approach for these different scenarios and instances. Some possibilities are:

- Scalability: a possible explanation is that the OR-Tools tool can run in the cloud, having a much larger processing and storage capacity than the system implemented on a single computer or server. In this way,

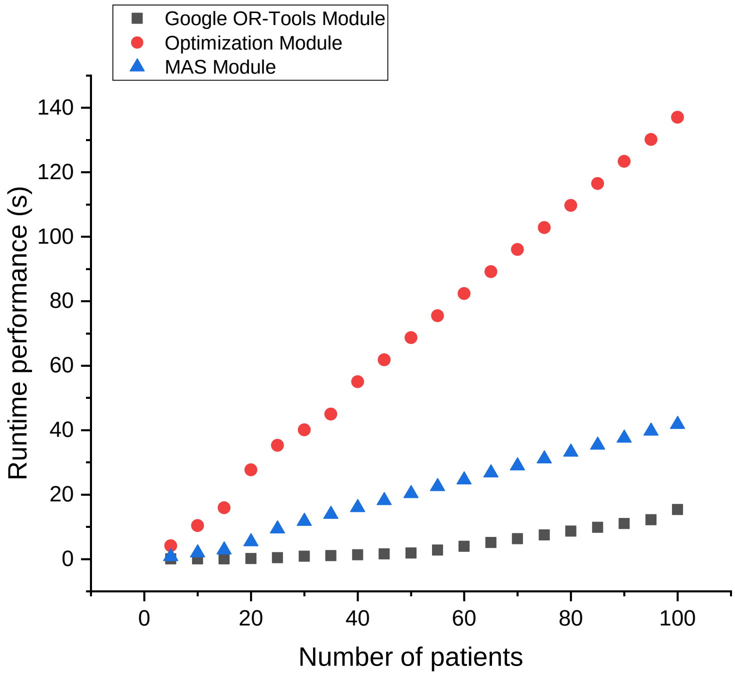

Figure 57: DOCtoR performance.

the tool is able to deal more quickly with the scenarios considered.

- Better integration with the platform: it is possible that the OR-Tools tool was better integrated with the platform used in its decision support system, which may have allowed for more efficient communication and faster and more accurate information exchange.

Despite the many theoretical advantages observed in the previous chapter by the application of metaheuristics and MAS, the practical execution of these methods may present limitations. In this sense, it is possible to verify that perhaps the communication paths between the prototype and the integrated modules could affect the system execution time. The use of different communication protocols (TCP/IP to connect to the MatLab software and HTTP to connect to the JADE platform) can have an impact on the data transmission speed between the modules (low throughput in networks with some/high latency), as well as on the network bandwidth used and possible interruptions or delays in the connection. In addition, it may involve higher memory requirements and time to return the solution, especially from MatLab. Furthermore, it is important to consider that the efficiency of the system prototype depends not only on the quality of the optimization algorithms and agent models, but also on the wasy they are integrated and on the architecture of the system as a whole. In this way, it is possible that some modifications in the communication and integration of the modules can further improve the performance of the system.

In any case, these computational results raise questions about whether or not the quality of the solution (i.e., its result in practice, both in terms of times and route distances) was affected by the runtime of each solution approach. For this analysis, 8 simulations were performed, considering different instances of the routing and scheduling problem (e.g., 5, 24, 48 and 96 patients and their associated data). Real data from OSPM were used for the calculations of these simulations, however, more patients were added (randomly) to perform the total of the last simulation. Furthermore, real locations were used that took into account times and distances when simulating, so they may differ in later applications. Figure 58 presents, on the left, the first 4 simulations when the objective is to minimize the route in terms of time (minutes), and on the right, the remaining simulations with the objective of minimizing the route in terms of distance .

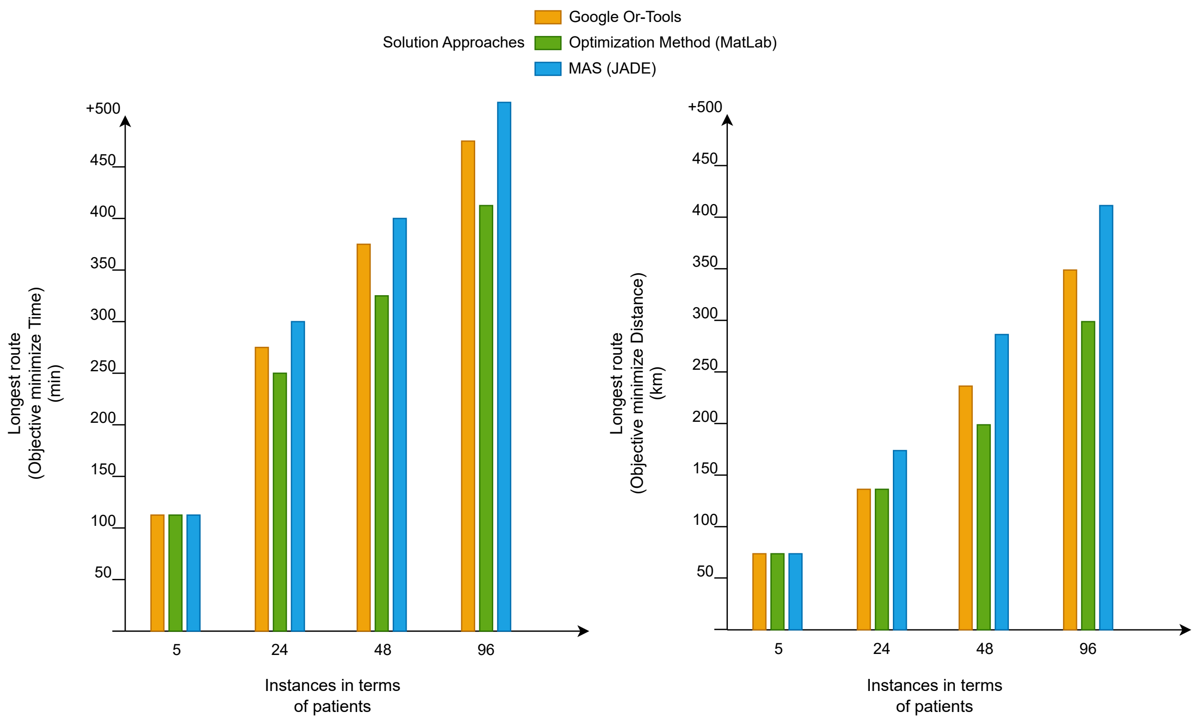

Figure 58: DOCtoR results in terms of the quality of solutions.

In these simulations, the results showing the minimization of the longest route were adopted, which in itself already reveals the quality of the solutions and the workload balance between the available resources and the needs of the patients. In order to standardize the different scenarios, for the simulation with 5 instances only one care worker and one vehicle were used, in the simulation of 24 patients 2 care workers and 2 vehicles were used, in the simulation of 48 patients already accounted for 3 care workers and 3 vehicles and finally, in the simulation with 96 instances 4 care workers and 4 vehicles were available. For the results whose objective was to minimize time, the solutions account for the time to to depart from the origin, provide services to patients, and return to the point of origin. In turn, when the objective of minimizing the distance was chosen, only the number of kilometers necessary for the route was counted.

These results are very interesting, because they allow us to check some indicators of efficiency and effectiveness of solution approaches (KPI). These indicators always depend on the needs of OSPM, which, for example, may want to reduce fuel costs, that is, the indicators need to take into account the solutions that have a shorter distance in prevalence than other indicators. In turn, if time is decisive, the same happens with the indicators that need to meet it. The ultimate goal is always to increase efficiency (serving the greatest number of patients by spending the least amount as possible) and effectiveness (planning the solution to the computational problem in the shortest possible time).

If the runtime KPI is taken into account and if a Figure 57 is remembered for instances of 5 patients, the computational time to obtain the solution does not present a considerable difference and the result in terms of efficiency (solution quality) practically obtained the same results (Figure 58 on both sides). Thus, it can be stated that, for small instances, the decision-making of the manager for any of the solution approaches would be optimal. If we take into account the number of patients (24) equal to the study scenario of the app DOCtoR, some differences appear. With this number of instances, there are considerable differences, in terms of performance, as the optimization module already needs about 20 seconds longer to reach the solution (Figure 57), when compared to the other solution approaches. In turn, regarding the quality of the solution, the optimization module minimizes the time and reveals a better solution efficiency capability (14% less than Google OR-Tools and 29% less than the module MAS). The difference involves more than 25 minutes for the longest route through two solution approaches. However, the differences are very noticeable if simulations with more instances are considered. If, for example, 96 patients are taken into account, the runtime performance varies greatly for the 3 solution approaches. In practical terms, it means that the optimization module needs about two minutes to solve and present the solution when compared to other approaches that need less time. On the other hand, also with this number of instances, the efficiency of the solutions is also largely affected, as can be seen in Figure 58. Once again, the optimization module enables better quality solutions with savings of more than 15%. The difference between the solutions obtained is more than 1 hour in terms of time and more than 50 kilometers, which could be a decisive factor.

These KPI are important to validate and can become decisive factors in decision-making. However, it should be noted that, considering that most of the planning at OSPM is carried out casually, that is, day by day or week by week, the importance of indicating computational performance will be less important compared to the quality of the solution approach. However, But if there is forgetfulness or emergency planning (which is happening more and more and these emerging needs can be verified by the COVID-19 pandemic), the decision-maker will have to be able to combine indicators appropriately, taking into account priorities in dynamic events. Furthermore, if there is a need to reschedule an unexpected patient on a route in real-time or readjust a given route to a new (available) vehicle due to a breakdown, MAS is undoubtedly an inherent advantage of the prototype, so that with minimal human intervention, it can suggest a reactive yet intelligent solution for the application.

The main objective of the overall solution is to help in the planning process of visits and also to calculate optimized routes to reduce the duration of routes and shifts, to promote the balance of workload among the care worker team, to improve efficiency and effectiveness, and to empower all staff. The digitalization of business processes and the adoption of new technologies (smart approaches) can also automate operational processes and enable cost reduction. The DOCtoR system brings reduction from an economic point of view and improvement from an efficiency perspective. Furthermore, the use of new technology has the potential to increase the efficiency and effectiveness of institution's business, reduce route calculation times, and optimize visiting shifts and distances travelled, all with an impact on costs. The resources saved enable the IPSS to invest in new equipment, infrastructure, cloud technologies and vehicles, allowing it to expand service coverage.

6.4.3 Usability Test Results

When reporting results of usability tests, the focus should be primarily on findings and recommendations that are differentiated by severity levels.

The initial version of the system was recently delivered (late 2022) to the home care service manager in OSPM. The main purpose of the meeting was to discuss the prototype, its flow, features and its benefits. The home team manager was tasked with performing a set of experiments to get feedback on the prototype (Figure 59). Since the Web/app applications already have real patient information, the manager tested the application by simulating the planning and calculation of a real route.

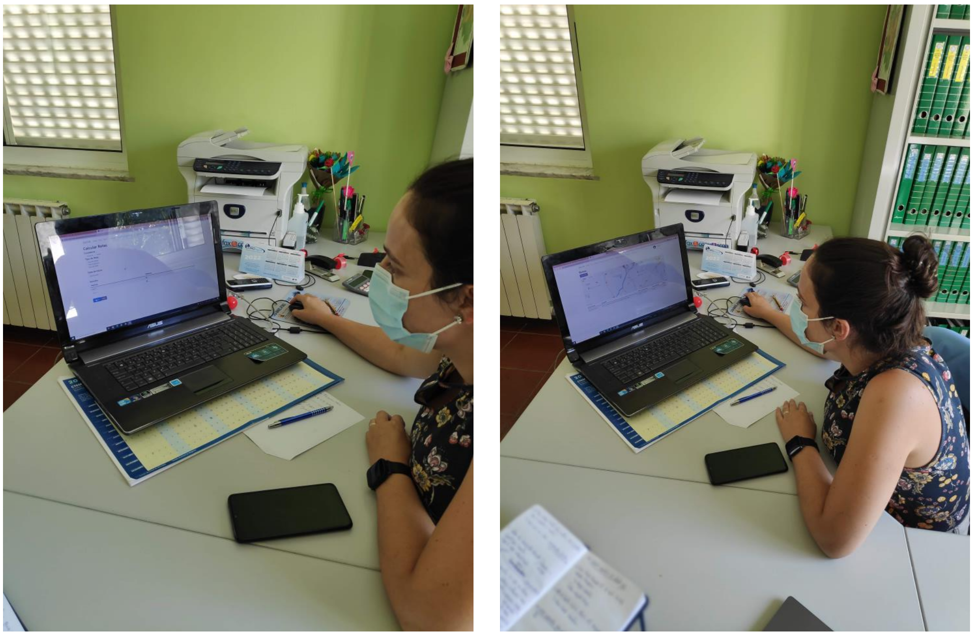

Figure 59: Interaction of the OSPM home care service manager with DOCtoR and use of its resources.

In simple terms, app usability refers to the ease with which a user can interact with the app and use its features. In terms of KPI, the time spent in the app, frequency of use, repeated use and exit rate will be measured. The conveniences, easy communication with care workers, and online usage will be tested in a real-world environment, to make the user experience more accurate.

However, after a few months of use, the manager collected data on feedback and usability, revealing that effectiveness, satisfaction, learnability, interactivity, and involvement were ranked as the main attributes for both internal responsible IPSS users and DOCtoR consumers (staff workers). This satisfaction concerns the user's comfort and enjoyment, as well as the importance of ease of use and intuitiveness. Furthermore, portability and compatibility (with mobile devices) were important considerations when handling the apps. The information was provided in a timely and reliable manner, with no evident errors or bugs, and was integrated into daily planning with a user-friendly interface. More specifically, the experimental tests generated reliability in the DOCtoR prototype and its capabilities to optimize routes and allocations compared to the existing process (in addition to generating different replacement options), which has implications in terms of associated costs as well as time savings in data management. These characteristics led to positive feedback and framed the HHC goals, responding to needs, and offering a comprehensive and visible development with the IPSS core target.

In general, the OSPM staff group increased workflow efficiency, streamlined schedule communication, and increased staff morale with DOCtoR. With intelligent automation in place, providers now trust that their schedules are accurate and fair. Alongside improved scheduling, they also gained these benefits:

- 30% reduction in time and distance: significant reduction in time to build and manage schedules. DOCtoR allowed the group to see when they would be understaffed or overstaffed based on demand patterns during previous time periods and where the solutions outperformed the solutions produced by the OSPM planners in terms of costs (saving potential);

- Improved performance: empowering staff through autonomous scheduling and routing. DOCtoR improves provider utilization by scheduling the appropriate number of providers per day, reducing overtime spend or costs associated with pulling in last-minute resources;

- Enhanced quality of delivery and care worker satisfaction: DOCtoR easily incorporates all pairing rules/skills for OSPM staff providers. Accurate ratios of providers scheduled through DOCtoR improve care workers satisfaction and freeing up time for users to focus on other issues;

- Accommodation of varied constraints and restrictions: easily deals with the complexities that lie within the variability of care (real-time visit locations, time and distance matrix, treatments and skills provided, vehicles, schedules and routes);

- Improved data analytics and reporting: DOCtoR requesting and reporting tools dramatically improved the easier access to data, management and monitoring, data collection in many forms, as well as ensuring service optimization with minimal human intervention.

The web/mobile workforce management functionality of a DOCtoR solution provides access to information anywhere and everywhere, which empowers manager and care workers in many ways. It could be new information about a patient, a cancellation, mobile training, or even a real-time traffic update to help the service arrive on time for an appointment.

In addition, the DOCtoR solution can also help all staff in the field feel more connected to the organization, helping to increase employee satisfaction. As a recruiting tool, DOCtoR system helps to relieve the frustration of outdated or inefficient processes that stand between your team and the work they truly care about doing. Spending time on unnecessary paperwork or on the road following poorly planned routes can lead to dissatisfaction with the job and has the potential to discourage new hires from joining a firm in the first place. “In the future we will switch to the DOCtoR system because all of the functionalities are aligned with our scheduling and routing needs, since everything could be handled on the computer, and because of the time savings associated with building and maintaining the operational planning”, said the manager of the OSPM, responsible for the home visits department. “Staff can now access the schedule from home via their smart devices, reports can be run quickly and easily, and routes are now calculated and optimized in DOCtoR, replacing cumbersome manual efforts”.

Some concerns were also raised, specifically about infrastructure charges (which are currently free) and regular updates with consumer needs (which are still in the experimental phase), when combined with the latest technology and ads in applications. Future improvements and experiments were also suggested, both qualitatively and quantitatively, in terms of requests for planning and routes involving a large number of patients (e.g., more than 80), as well as the attachment of real-time information for the arrival and departure of the home care team. Efficiency will be evaluated to generate meaningful insights and learnability reports will be created to provide regular instruction on how to use devices for people with little digital skills. Furthermore, it will be important to improve and optimize the Transmission Control Protocol/Internet Protocol (TCP/IP) performance throughput (assuming a reasonably error-free transmission path), where the sender should send enough packets to fill the logical pipe between the sender and receiver, preventing some delays in communication with the optimization module.

Based on these findings, and taking into account the average time, the API instances will need to be sized in order to prevent the average time from increasing further and to allow the prototype to be used in all real-world home care situations. It will also be important to eliminate issues of inconsistency, undesirable outcomes, suspected bugs, and reduce limitations on requests to external microservices (e.g., Google Distance Matrix API).

In the end, these usability tests were structured to adjust and meet the future needs of OSPM, the possibility of recruiting new participants, designing new tasks and analyzing the new insights. This situation is likely to happen as increasing numbers of home healthcare/social organizations discover the value of optimization and automation as competitive differentiators to improve success rates.

6.5 Summary

Given that OSPM is responsible for 86 patients, one can imagine how time-consuming, hard and can lead to erroneous estimates, long routes and poor allocations (especially when it is only performed by the manager, without computational support and only with its empirical knowledge) the planning and assignment of tasks to the staff to do all these visits. The prototype DOCtoR intends to cover and offer a dynamic and optimized collaborative system for route recommendation, that provides high quality solution(s) for the planning problem of the OSPM, supporting complex decisions in route management networks, the allocation of professionals, guidelines and daily support for decision-making. The system infrastructure offers quick responses and solutions, dynamic adaptation, and decentralized control, containing, for this, a distributed collaboration between ICT technologies, data digitalization, MAS and optimization methods for supporting decision-making in the IPSS. The system has two main components: a web application, designed for the home care manager, that manages and plans the visits; and a mobile application specified for the care workers team that performs the visits. Thus, the primary goal of this prototype was to optimize the route planning process in order to reduce the institution's economic and time costs.

7

Conclusions and Future Work

"Success is not final, failure is not fatal: It is the courage to continue that counts." - Winston Churchill.

With the world stuck in the middle of a pandemic, health and social systems are looking to ICT to shift the balance of care outside the hospital, clinic, or social organizations and into the home. As countries around the world face increasingly aging populations, the HHC problem is only destined to grow in severity. This strategy focuses on the operational HHC service, which has long balanced connected and in-person care, but, faced with a shortage of providers and a growing surplus of patients, could use more of the former and less of the latter. In addition, as seen in the context of the Covid-19 pandemic, it is urgent to train and modernize the current health service structures, integrating optimized systems to better support professionals and technicians. Decision support systems (*mHealth*) and connected devices are needed to digitalize operational data and planning, remote patient monitoring, provide a continuous care experience, and a balance between care and social support. However, with the constant emergence of care, the benefits of organizations providing home care have been few, which continue with strategic and operational planning policies carried out manually, without computational support or practical ways of replacement. This implies increased fatigue for care workers and management offices, a poor workload balance, and increased costs with inefficient routes and schedules. Thus, as technology progresses at an ever-rapid rate, the potential to transform HHC will grow and organizations will be able to deliver increasingly exceptional levels of patient care, process efficiency, encourage greater caregiver satisfaction and improve cost control.

The problem studied in this thesis, refers to complex scheduling and routing problems that occur in several everyday situations, giving special focus to the HHC services, their characteristics and needs. The objectives and research questions were presented, supported by a scientific research methodology that strengthened the work. A literature review was first conducted to identify the state of the art, most commonly used scheduling and routing methods and strategies for solving the HHC problem. Thus, optimization models and methods were discussed, where different approaches are detailed to explain how they can integrate into a design of an optimized module. MAS was the technology studied to enable a smart and reactive solution, and theoretical concepts in the hybridization of combined approaches were also investigated.

Mainly promoted by the digitalization and distributed solutions, a general guideline was designed to address an architecture capable of addressing the main aspects and concerns that should be considered during strategic and operational planning in HHC. This architecture comprises a set of modules that define different and/or complementary tasks, as well as their interactions and strategies to support decision-making, even in unexpected events or time-sensitive scenarios.

The main modules integrated in the architecture (engines) were implemented and evaluated in different experiments (some with real scenarios from the Santa Maria Health Unit), in order to demonstrate and test the applicability and some aspects (separately or in hybrid approaches) of the proposed infrastructure. Based on this, it was sought to support on a solid and capable basis through a prototype (DOCtoR) developed for an institution in Portugal that provides home care services (OSPM). The DOCtoR combines different optimization methods and smart agent models, which combined in a digital infrastructure, support management and decision-making of the home care service. The integrated system allows, through collaboration tools, to have a currently improved response, in a timely and effective manner to scheduling and routing monitoring. In addition, the tool had essential resources involving different methods, cloud solutions, and support software, essentially based on a web and mobile application to decentralize and balance information analysis for the home care team.

In summary, this thesis proposes and contributes to a distributed architecture with multidisciplinary modules integrated into an infrastructure that works collaboratively between an MAS, optimization strategies and decision-making support based on a digitalized platform for scheduling and routing planning in real contexts of HHC services. A set of validation experiments were designed, which contributed to the development of the DOCtoR prototype, highlighting its applicability in different contexts. Furthermore, this research work also attempts to promote some of the objectives of the United Nations Sustainable Development Goals (2030 Agenda), in the sense that it seeks to ensure healthy lives and promote well-being for all at all ages and build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

The remainder of this chapter is structured in two sections. The first summarizes the main contributions in order to answer the research questions, and discusses and critically reviews the results that were obtained throughout the work carried out to achieve the objectives of this thesis. The second section points out future work, briefly discussing some promising research opportunities and how they could contribute to improve and evolve the work developed in this thesis, as well as related research challenges.

7.1 Main Contributions and Critical Review

The main contributions of this work are the three parts of the proposed conceptual framework, comprising the agent-based module interconnected with the optimization module, and these two form an integral part of an architecture of a system based on an interface module that processes the data, performs requests, manages information, and visualizes/monitors results and solutions. The investment in the different experiments was also a major part of the research of this work, not only for its validation but also to make sure that the technologies and multidisciplinary areas would be well aligned. Thus, models and methods capable of building and optimizing routes and planning of home services in the region of Bragança, Portugal, were developed, solving a complex and combinatorial problem, considering multiple constraints of the problem itself. In this sense, two case studies were conducted, in the Health Unit of Santa Maria, in Bragança, where multiple experiments were carried out with the experimental dataset, and another applied to OSPM, the latter with the application of a prototype in a real context. In addition, the developed DOCtoR system provides a general guideline to support a customized decision-making on the needs of HHC problems with the support and decentralized analysis of data and solutions.

In this context, the research questions, defined in Section 1.2, guided the work proposed and discussed in the different chapters, will now be the subject of a structured analysis and a conclusive answer.

RQ-1: How to improve decision-making support with faster and more dynamic solutions in HHC scheduling systems, while maintaining an optimized performance?

Healthcare organizations are currently facing increasing pressure to deliver high-quality care at an affordable cost while still complying with increasingly complex government regulations. In today's world, where time is of the essence, it becomes more and more important to have quick and efficient communication platforms. To meet these challenges, healthcare providers must implement effective management systems to optimize their clinical and operational resources and ensure that they provide the best possible care to their patients. An area that can be optimized to improve the efficiency and effectiveness of care delivery is home care scheduling and routing, balancing the conflicting goals of meeting patient needs in a timely manner while ensuring efficiency. Traditionally, home care scheduling has relied on manual processes to plan patient care and allocate resources, often resulting in significant delays and inefficiencies. This has led to an increased demand for automated solutions that offer efficient, reliable, and seamless patient scheduling solutions while maintaining a high degree of flexibility and customization. Furthermore, HHC services urgently need to be modernized in their planning and operation, devoid of digital resources that could improve user satisfaction, interactions with information and leverage an optimized and digitalized management policy that allows expanding patient support coverage.

Taking all this into account, the answer for this question required the execution of several tasks, leading to the specification of the proposed architecture, which involves a set of integrated and multidisciplinary modules with specific roles, which is one of the main contributions of this work. This work outlines some of the challenges that healthcare providers face when implementing new processes and how decision-making based on MAS combined with optimization methods and supported by a digital monitoring platform can overcomes them to provide a new solution that is flexible enough to meet different service needs. Thus, how these challenges were addressed by applying these areas to the digitalized tools and workflows used by healthcare workers who were part of the ICT platform was described.

The various tasks involved allow the system to combine the strengths of multiple distributed agents to implement an efficient scheduling and routing strategy for the healthcare organization, especially in emergencies where fast and smart solutions are needed. In addition, the system centrally obtain optimal solutions for operational planning using optimization models and methods (e.g., metaheuristics procedures). Each information management task is particular and can be successfully managed through a customized application that communicates with the other components of the system using a lightweight communication mechanism. Thus, based on the results obtained in Chapter 5, it was demonstrated that combining optimization methods with MAS shows innovative capabilities that contribute to digitalize and assist better planning and decision-making in HHC systems and services. In this sense, it was proved that, for example, the MAS module can be used to coordinate and replan routes and schedules in unforeseen situations, taking into account changes in resource availability, while the optimization system can be used to find the best scheduling solutions in deterministic and more predictable scenarios. Taking these factors into account, with the hybrid approach an effective and efficient balance can be obtained that offers sustainable and viable dynamics for the real logistics of the HHCSRP.

Although the main objective of this research question is the improvement in decision-making support in HHCSRP, which was achieved, it is possible to relate this support system to the use of the DOCtoR system by users. To improve decision-making support, it is important to ensure that users have access to accurate and up-to-date information, as well as tools and resources that can help them make more informed and effective decisions. Digital technology can provide a suite of solutions to address these needs, such as automating scheduling processes, integrating data from multiple sources into a single location, and advanced data analytics. Furthermore, to maintain optimal performance, it is important to ensure that these digital solutions are fast and dynamic enough to handle the ever-changing demands of HHC services. ICT based on *mHealth* applications characterize the next generation of distributed and intelligent automation systems for health services, mainly in operational and logistic needs. Furthermore, the proposed approach uses ICT and specific tools, aiming to be compliant with the widely used standards and consequently supporting a better interoperability with other components, e.g., that have been employed in the digitalization and automation of HHC. Considering these advantages, the use of ICT technologies was presented and described, in particular concerning the user interfaces (UI), taking into account the application of DOCtoR. In the real context of OSPM, users were asked to rate the ease of use of the system (based on feedback and their own observations), as well as the impact of ICT technologies on the efficiency and accuracy of tasks. The feedback received was detailed in terms of concrete examples of improvements in the efficiency of the scheduling and route allocation process. Thus, it was demonstrated (Chapter 6) that the use of the system allowed to have the advantages of: greater efficiency in automating repetitive tasks and greater efficiency in the process of scheduling and allocation of routes; improvement of accuracy, where human errors are minimized and an attempt is made to ensure the accuracy of the data, resulting in more informed and accurate decisions; better communication between care workers, service manager and health facility, leading to better coordination of care and a more positive overall experience for all involved; greater transparency, as they offer users a complete view of the scheduling and route allocation process, allowing them to follow the status of their tasks in real-time; ease of access, which through web and mobile interfaces allow users to access the scheduling and route allocation system anywhere and at any time, which can improve the efficiency and flexibility of the process. However, it is important to note that subjective user feedback may be limited in its ability to provide a complete picture of the impact of ICT technologies and the user interface on the process of HHC scheduling and routing.

RQ-2: What are the main design aspects and criteria that should be considered to support user decision-making regarding deployment, computational time and quality of solutions?

This question was defined to address a complementary need that was expected from the result of the first question, that is, given a customized architecture, how can the different solution approaches be evaluated, at which moments are they more relevant and, at which point can they support decision-making in the operational planning of HHC. The increasing demand for home healthcare services has led to the development of routing and scheduling solutions that can optimize patient care. These services should support users (managers and care workers) in making decisions based on multiple parameters (e.g., efficiency, cost, quality, among others) in order to reduce unnecessary transport trips and support efficient resource allocation. This work answer and explores several design aspects that should be addressed in the design of home healthcare routing services. It also considers several criteria to evaluate the performance of such solutions. HHCSRP managed to be solved using systems that helped to reduce unnecessary trips between patients and their healthcare providers by improving the mobility of care workers. Such systems have reduced transportation costs by enabling caregivers to travel more cost-efficiently and perform their tasks more efficiently. Routing systems also helped to improve patient care by allowing patients to receive timely care from their preferred caregivers while reducing travel time between them.

The different tests showed that basically, for planning without unexpected events, the optimization methods, as a whole, are able to return in a reasonable time an optimal solution capable of being put into practice. Furthermore, when the system is subjected to an unexpected event (emergency, broken vehicle or a new patient), the agent-based model has the ability, autonomously and almost instantaneously, to react and readapt, suggesting "optimized" alternatives to stabilize the system. The solutions of the hybrid experiments allowed to verify that the combination of optimization methods and MAS allowed to reach the best situations: the intelligent control, cooperation and autonomy provided by MAS solutions and the optimum offered by optimization methods. Furthermore, the combination of these strategies in a hybrid way allows to achieve better results in terms of performance criteria, responsiveness and autonomy level in coordination with real experiments.

Although this approach showed to be robust to map the experts knowledge and reduce the complexity required to evaluate many criteria, it needs to be defined considering specific real-time application scenarios. In order to create an even more meaningful purpose for this research, the prototype DOCtoR was developed, to evaluate the research proposals for the design of the eventual product by actually trying them out, rather than having to interpret and evaluate the design based on descriptions. Thus, all software functions and potential threats or issues were grouped together. The system, in general, is supported by API that connects the various integrated modules, focusing on an innovative web and mobile platform (*mHealth*) to offer dynamic and optimized routes, allowing access and management to the database and visualization and monitoring of the plans. The deployment of the framework in a real environment allowed all OSPM information to be storedwithout delays and allowed the user to choose the best solution approach given the knowledge received. Thus, a dynamic and distributed system was provided, which allows the user to describe and prove requirements, access and modify constraints and deliver distributed and optimized solutions that interact with care workers and benefit the quality of care provided to patients in their homes. Furthermore, DOCtoR makes suggestions for the most efficient routing and care worker choice when new appointments arrive, improves the workload, reduces time and costs, and improves and increased user involvement and satisfaction.

Based on the research, it was possible to conclude that the main aspects and design criteria to successfully support the user decision-making regarding the deployment, computational time and quality of the solutions for HHCSRP, include:

- Flexibility and adaptability of the architecture: the architecture was able to adapt to the needs of users and health institutions, allowing the implementation of different types of home services and their requirements.
- Decentralization and distribution: the interconnected architecture with different modules, optimized and distributed, guarantees the scalability and resilience of the system.
- Optimization and resource management: the architecture demonstrated the ability to manage and optimize available resources, including efficient task allocation, to ensure the quality of service and reduce computational time.

- Responsiveness in case of disruptions: the module MAS highlighted due to its reactive capabilities and smart responses in case of unexpected events.
- User Interface: the user interface proved to be user-friendly and easy to use, allowing users to view and manage home services, routes and schedules.

Continuous evaluation and monitoring of the solution will be important to ensure its effectiveness and Thus, through the collection and analysis of data in real-time, the system allows adjustments and continuous improvements in the solution of routes and schedules, and security and privacy measures to guarantee the protection of user data.

Finally, it is important to highlight some usability metrics in the testing of the DOCtoR prototype, which is a subjective way allowed to assess the efficiency, effectiveness, user satisfaction and ease of use of the system. The solution improved the user experience, such as reducing service fees, simplifying access to real-time information and making it easier to manage routes and schedules. The results proved to be promising since the solution can be scalable and customizable for different user needs, allowing them to adapt the solution to their specific requirements.

As discussed in the answers to the above research questions, the results obtained in this work contributed to achieve the objectives of this thesis, as well as to confirm the hypothesis defined in Section 1.2 and repeated here:

> "Optimization algorithms combined with MAS approach can provide a modular and flexible architecture to design and develop distributed and collaborative scheduling and routing applications, endowed with a database and dashboard for monitoring modules, that can be deployed along cloud or mobile apps, in order to address the different objectives of the HHC planning and management."

When it comes to caregiving, everyone knows that there is no one-size-fits-all approach. In fact, the right care plan for one person may not be ideal for another. For this reason, it is important to create a personalized care plan that meets the specific needs of the individual. The requirements involved in designing optimal scheduling and routing protocols for automatic systems in the healthcare domain are complex, therefore, new ways must be found to address these challenges. Furthermore, a web/mobile workforce management tools are no longer a nice-to-have, but rather a competitive differentiator that all home care providers (or other service industry) should deploy. The first version of DOCtoR was presented to the OSPM manager, and the obtained feedback was very positive and indicated that the institution can adopt the solution as soon as it was completed.

In summary, this research and solutions can support complex decisions in the management networks of schedules and routes in HHC, allocation of professionals and inventories, guidelines and support the decision-making to improve its service efficiency and reduce costs with route planning.

7.2 Future Work

There are many challenges in addressing these kinds of combinatorial problem, especially in the HHCSRP. Although there are numerous ways to improve and extend the proposed work, the following are some research opportunities and ideas that are thought to be the most interesting and promising in the future. They are organized into groups based on the main components of the proposed architecture, experiments and DOCtoR prototype.

Based on the designed architecture and its integrated modules, they are classified according to the key components of the application. Therefore, it can be improved by further specifying the collaborative mechanism that can be used by each module, separately. Considering the optimization methods and models, different and more robust objectives can be included in the future, namely stochastic situations in real-time or travel balancing beyond the work time balance, making the model more complex and interesting. Perhaps one could contribute to machine-learning algorithms as very useful criteria for providing a simulation model for HHC activities. Last but not least, the application and development of a new model based on CG could be very interesting in the future, as long as the computational effort continues to be worthwhile.

Future work prospects related to MAS module, can involve the analysis of other parameters for the negotiation process, such as proposal load balancing, trust, and confidence in decision-making. It might also be interesting to add to the agent model, AI techniques to identify errors made by the user automatically and efficiently according to the exercises performed. In the agents module, it will also be interesting to include functionality that can involve the organization in the decision process.

In addition, other scenarios and experiments should be designed and performed in order to evaluate the features and benefits of the module. To achieve this, some research challenges may include the identification of the existing collaboration mechanisms and protocols, their application scenarios, and consequently the definition of a general guideline to indicate how they should be used to address specific application requirements and constraints.

Regarding the DOCtoR, the next step will involve software continuous integration strategies for updates and will be included in order to minimize the impact on user usability, ensuring that the application runs without interruptions or crashes. It will be important for the next steps to create relevant performance metrics and more objective evidence, such as the rate of visits completed on time, the reduction of patient waiting time and the optimization of the use of available resources so that in future work they will be used to assess the impact of ICT technologies. Future work also involves the improvement of the implemented solution to overcome some limitation identified in the Google Distance Matrix API, which only allows 24 requests at a time. It was necessary to create a mechanism to add the request and increment it to the matrix, but it probably increased the response time, so in the future it will be important to overcome this limitation in a smarter and more optimized way. Furthermore, security aspects with clinical information will be important for the entity to maintain the confidentiality and privacy of patient data, namely through strong authentication methods, regularly installing security patches and updates, and prioritizing Wi-Fi connections or secure virtual private networks (VPN).

Related to patient-care worker engagement, in the future the delivery high-quality care or services will be increasingly important, especially in contexts like the one we experienced in the COVID'19 pandemic. Not only does this mean having highly trained professionals to deliver care, but also contributes to improving patient experiences. In this on-demand economy where service is available at the push of a button, patients now expect and demand a level of real-time communication and visibility, through platforms that combine, e.g., teleassistance. There is no doubt that digital applications are becoming increasingly popular in both the general population and within the healthcare industry. The reasons for this are many, but are mainly due to the convenience and accessibility they provide, as well as their range of capabilities (from monitoring patient vital signs to facilitating communication between patients and clinicians or care workers). In the future it will also be important to evaluate the current technologies, as they tend to be quite bulky and expensive and as such it can often be a challenge to ensure that patients are able to use them without assistance or that they are able to store the data that is being collected safely for future use. In terms of institutional management, it may be interesting in the future for DOCtoR to perform not only through mobile workforce management but also through real-time updates, such as the location of the care workers and an estimated time of arrival at the appointment.

In summary, from now on it will be extremely important to take into account the growing adoption of *mHealth*, wherein the user uses cell phone applications and other smartphone capabilities to access or analyze health information, adherence reminders, and lifestyle monitoring.

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A

Details of the Dissemination Results and Awards

This appendix presents the dissemination of research results, through published articles, as well as honors some awards.

In doctoral work, it is normal to produce a substantial number of research results. For these results to benefit society, they must be made available to relevant people and used to generate further impact. Therefore, it is important to list the works that have been distributed through scientific publications since the beginning of the PhD work and other articles that are ongoing for future publication.

Regarding journal articles, the following were published:

- Alves, F., Varela, M. L. R., Rocha, A. M. A., Pereira, A. I., & Leitão, P. (2019). A human centered hybrid MAS and meta-heuristics based system for simultaneously supporting scheduling and plant layout adjustment. FME Transactions, 47(4), 699-710. https://doi.org/10.5937/fmet1904699A [5]

- Alves, F.; Costa, L.A.; Rocha, A.M.A.C.; Pereira, A.I.; Leitão, P. The Sustainable Home Health Care Process Based on Multi-Criteria Decision-Support. Mathematics 2023, 11, 6. https://doi.org/10.3390/math11010006 [21]

- Silva, A.S.; Alves, F.; Diaz de Tuesta, J.L.; Rocha, A.M.A.C.; Pereira, A.I.; Silva, A.M.T.; Gomes, H.T. Capacitated Waste Collection Problem Solution Using an Open-Source Tool. Computers 2023, 12, 15. https://doi.org/10.3390/computers12010015 [182]

In terms of book chapters, the following works were published:

- Alves, F., Pereira, A.I., Fernandes, A., Leitão, P. (2018). Optimization of Home Care Visits Schedule by Genetic Algorithm. Bioinspired Optimization Methods and Their Applications. BIOMA 2018. Lecture Notes in Computer Science, vol 10835. Springer, Cham. https://doi.org/10.1007/978-3-319-91641-5_1 [17]

- Alves, F., Pereira, A.I., Barbosa, J., Leitão, P. (2018). Scheduling of Home Health Care Services Based on Multi-agent Systems. Highlights of Practical Applications of Agents, Multi-Agent Systems, and Complexity: The PAAMS Collection. PAAMS 2018. Communications in Computer and Information Science, vol 887. Springer, Cham. https://doi.org/10.1007/978-3-319-94779-2_2 [19]

- Alves, F., Varela, M.L.R., Rocha, A.M.A.C., Pereira, A.I., Barbosa, J., Leitão, P. (2020). Hybrid System for Simultaneous Job Shop Scheduling and Layout Optimization Based on Multi-agents and Genetic Algorithm.

In: Madureira, A., Abraham, A., Gandhi, N., Varela, M. (eds) Hybrid Intelligent Systems. HIS 2018. Advances in Intelligent Systems and Computing, vol 923. Springer, Cham. https://doi.org/10.1007/978-3-030-14347-3_38 [11]

- Alves, F., Rocha, A.M.A.C., Pereira, A.I., Leitao, P. (2019). Distributed Scheduling Based on Multi-agent Systems and Optimization Methods. In: , et al. Highlights of Practical Applications of Survivable Agents and Multi-Agent Systems. The PAAMS Collection. PAAMS 2019. Communications in Computer and Information Science, vol 1047. Springer, Cham. https://doi.org/10.1007/978-3-030-24299-2_27 [10]

- Azevedo, B.F., Alves, F., Rocha, A.M.A.C., Pereira, A.I. (2021). Cluster Analysis for Breast Cancer Patterns Identification. In: , et al. Optimization, Learning Algorithms and Applications. OL2A 2021. Communications in Computer and Information Science, vol 1488. Springer, Cham. https://doi.org/10.1007/978-3-030-91885-9_37 [28]

- Alves, F., Rocha, A.M.A.C., Pereira, A.I., Leitão, P. (2021). Multi-agent System Architecture for Distributed Home Health Care Information Systems. Technological Innovation for Applied AI Systems. DoCEIS 2021. IFIP Advances in Information and Communication Technology, vol 626. Springer, Cham. https://doi.org/10.1007/978-3-030-78288-7_28 [12]

- Alves, F., Pacheco, F., Rocha, A.M.A.C., Pereira, A.I., Leitão, P. (2021). Solving a Logistics System for Vehicle Routing Problem Using an Open-Source Tool. In: , et al. Computational Science and Its Applications – ICCSA 2021. ICCSA 2021. Lecture Notes in Computer Science, vol 12953. Springer, Cham. https://doi.org/10.1007/978-3-030-86976-2_27 [20]

- Alves, F., Rocha, A.M.A.C., Pereira, A.I., Leitao, P. (2022). Multi-agent System Specification for Distributed Scheduling in Home Health Care. In: Borangiu, T., Trentesaux, D., Leitão, P., Cardin, O., Joblot, L. (eds) Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future. SOHOMA 2021. Studies in Computational Intelligence, vol 1034. Springer, Cham. https://doi.org/10.1007/978-3-030-99108-1_6 [14]

- Silva, A.S. et al. (2022). Solving a Capacitated Waste Collection Problem Using an Open-Source Tool. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds) Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol 13378. Springer, Cham. https://doi.org/10.1007/978-3-031-10562-3_11 [181]

- Alves, F., Duarte, A.J.S.T., Rocha, A.M.A.C., Pereira, A.I., Leitão, P. (2022). A Hybrid Approach to Operational Planning in Home Health Care. In: Pereira, A.I., Košir, A., Fernandes, F.P., Pacheco, M.F., Teixeira, J.P., Lopes, R.P. (eds) Optimization, Learning Algorithms and Applications. OL2A 2022. Communications in Computer and Information Science, vol 1754. Springer, Cham. https://doi.org/10.1007/978-3-031-23236-7_9 [6]

- Alves, F., Rocha, A. M. A., Pereira, A. I., & Leitão, P. (2023). Conceptual Multi-Agent System Design for Distributed Scheduling Systems. In Smart and Sustainable Manufacturing Systems for Industry 4.0 (pp. 129-148). CRC Press. [8]

- Alves, F., Rocha, A.M.A.C., Pereira, A.I., Leitão, P. (2023). A Systematic Literature Review on Home Health Care Management. In: Innovations in Bio-Inspired Computing and Applications. IBICA 2022. Lecture Notes in Networks and Systems, vol 649. Springer, Cham. https://doi.org/10.1007/978-3-031-27499-2_15 [7]

- Silva, T.; Alves, F.; Pacheco, F.; Paiva, S.; Pereira, A. I. (2023). Dynamic and Optimized Collaborative System for Routes - a Case of Study in Home Healthcare. In: Fourth International Conference on Computing, Communication and Cyber-Security (IC4S-2022). Lecture Notes in Networks and Systems. Springer, forthcoming [184]

Finally, the following conference proceedings were published:

- Alves, F.; Costa, L.; Rocha, A.; Pereira, A. and Leitão, P. (2019). A Multi-objective Approach to the Optimization of Home Care Visits Scheduling. In Proceedings of the 8th International Conference on Operations Research and Enterprise Systems - ICORES, ISBN 978-989-758-352-0; ISSN 2184-4372, pages 435-442. DOI: 10.5220/0007565704350442 [23]

- Alves, F.; Alvelos, F.; Rocha, A.; Pereira, A. and Leitão, P. (2019). Periodic Vehicle Routing Problem in a Health Unit. In Proceedings of the 8th International Conference on Operations Research and Enterprise Systems - ICORES, ISBN 978-989-758-352-0; ISSN 2184-4372, pages 384-389. DOI: 10.5220/0007392803840389 [22]

- Alves, F.; Rocha, A.; Pereira, A.; Pereira, A. and Leitão, P. (2020). Automatic Nurse Allocation based on a Population Algorithm for Home Health Care. In Proceedings of the 9th International Conference on Operations Research and Enterprise Systems - ND2A, ISBN 978-989-758-396-4; ISSN 2184-4372, pages 395-402. DOI: 10.5220/0009386103950402 [25]

- Alves, F. et al., "Deployment of a Smart and Predictive Maintenance System in an Industrial Case Study," 2020 IEEE 29th International Symposium on Industrial Electronics (ISIE), Delft, Netherlands, 2020, pp. 493-498, doi: 10.1109/ISIE45063.2020.9152441. [9]

In addition to the international publications previously presented, the doctoral student was invited and given the opportunity to publish an article in the Portuguese Association for Operational Research newsletter:

- Publication of a news item for the newsletter of the Portuguese Association for Operational Research, within the scope of an article published every six months (number 64), with the title "Otimização de Rotas Periódicas num serviço de apoio Domiciliário", promoting Operational Research (OR) in Action (July 2021) - `http://apdio.pt/documents/10180/16684/Boletim_64.pdf`.

It should also be noted that the vast majority of these works are directly linked to the production of the research work described in this thesis, however, some publications are articles in the areas of research but not directly linked to the PhD, but initiatives of the host entities. In addition, there were also some (less relevant) works submitted and presented within the scope of project workshops linked to research centers, as well as seminars, poster initiatives, or meetings of young researchers.

During the research period, some applications for funded projects were also made, either to explore the value of the research work or to obtain a greater impact from it. Regarding applications, the following stand out:

- Application for the Foundation for Science and Technology (FCT) 2019 PhD scholarship, with funding approved for 3 years (reference SFRH/BD/143745/2019);

- Application for the "Altice INNOVATION award", which seeks to promote and recognize innovation, development and competitiveness in research (no funding);

- Submission of an innovative pilot project within the scope of the La Caixa Foundation program Promove, in the key topic of the research work, a scheduling and optimization system applied to the case study of Home Health Care (object of study in thesis validation). It comes in the course of the award received in 2019 (no funding).

- Applications for the "H-INNOVA health INNOVAtion HUB", "Alfredo da Silva Research Awards" and "Angelini University Award! 2020/2021". It was sought to promote and recognize the research imposed in the thesis. Note that the doctoral student won the public vote award at the 12th edition of the Angelini University Award! 2020/2021, with the title "Collaborative System for managing and monitoring healthcare at home through an app/digital platform and intelligent algorithms" (none had funding).

Furthermore, the following awards and distinctions were won/received:

- Application in partnership with a researcher and a professor at the La Caixa Foundation, according to the Promove initiative (2019), aimed at promoting innovative collaborative ideas and the dynamization of Portuguese border regions. The idea was based on some tasks compatible with the doctoral research ("HHC collaborative system for regions of low population density"), applied to the thematic domain of the creation or consolidation of new centers of specialization. Winning idea with award worth 5000 euros.

- Best paper award ("Deployment of a Smart and Predictive Maintenance System in an Industrial Case Study") in Session "Industrial Informatics and Cloud Computing" of the 29th IEEE International Symposium on Industrial Electronics (ISIE 2020), Delft, the Netherlands.

- Participation in the Doctoral Program in Industrial and Systems Engineering (DPISE 2021), member of the organizing committee, and active participation as a doctoral student ("Distributed Scheduling for a Home Health Care Information System"), where the Best Poster Award (value of 250 euros).

- Participation in the Workshop Doctoral Program in Industrial and Systems Engineering (DPISE 2022), with the presentation of the poster "Digital web/app system for home health care service management", where the award for best poster was obtained (value of 300 euros).

It should also be noted that several participations and coordination actions were carried out within the scope of funded projects (national and international) of the research centers allocated to the host entities. It is also important to note that during the research period, there was an opportunity to start teaching activities, supervision of extracurricular units, or research projects at the University of Minho and Polytechnic Institute of Bragança.

Over the years, some actions have been carried out to support the organization of multiple conferences, such as the International Conference on Optimization, Learning Algorithms and Applications (OL2A). Complementary training was also carried out at the University of Málaga and volunteering in the organization of the International Conference on Computational Science and Its Applications (ICCSA 2022), which also took place in Málaga.

These publications and awards were and are extremely important, not only because they have been applied in contexts and areas that are the focus of the PhD, but also because they were excellent communications in the domains related to the thesis.

B

Details of the Bibliometric Analysis Process used for the Literature Review

This Appendix presents the literature review focused on identifying the academic works (mainly journal and conference papers and articles) regarding some research topics related to this thesis. The Scopus and WoS databases were predominantly used in the search for these works, but there was also some recourse to the Google Scholar platform.

On the other hand, in order to identify the publication trends over the years and the concepts related to the research topics of interest, the Scopus and WoS collection shown to be more flexible, mainly when used in conjunction with the VOSviewer application [198], Bibliometrix R-tool and ScientoPy tool. The last two software had already been presented in Chapter 2, while the VOSviewer application appears here as a complement to the others. In turn, VOSviewer is a software tool for constructing and visualizing bibliometric networks. These networks may, for instance, include journals, researchers, or individual publications, and they can be constructed based on citation, bibliographic coupling, co-citation, or co-authorship relations. VOSviewer also offers text mining functionality that can be used to construct and visualize co-occurrence networks of important terms extracted from a body of scientific literature.

Based on that, some terms and queries were used to obtain information, regarding the number of scientific publications in the last years, that were used to create the Figures presented in Chapter 2. The queries were performed on October 2022. Additionally, they filtered the papers that are in the English language and also only considered documents of the types: Conference Papers, (journal) Articles, Book Chapters, Books, Reviews, and Short Survey.

In this follow-up, it was also essential to apply an even smarter search trick, in order to analyze the dataset results in terms of their subject area. The titles in Scopus or WoS are classified into broad subject clusters (life sciences, physical sciences, health sciences and social sciences & humanities), which are further divided into several main subject areas and minor subject areas. Figure 60 presents in visual terms the list of the main subject criteria associated with the pre-processed dataset.

Each criterion or area provides a unique and powerful way of understanding the results (search). Figure 60 allows covering several areas, where some represent a substantial portion of published research, e.g., computer science, engineering and operations research & management science.

In Figure 61, a network visualization in terms of co-occurrence keywords is presented. Co-occurrence is the

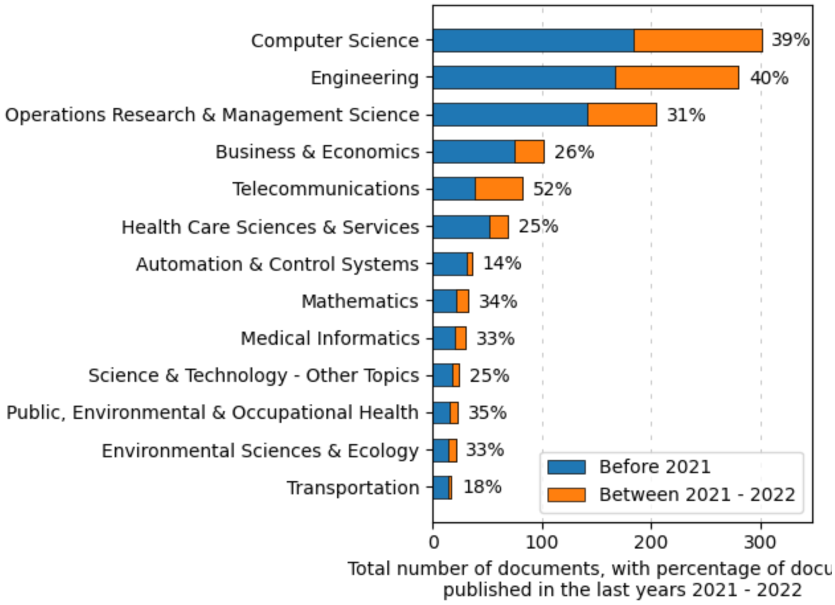

Figure 60: Analysis of subject criteria in a bar trends graph.

presence, frequency, and proximity of similar keywords across the dataset. Co-occurrence logically includes keywords that are topically relevant to the subject. These keywords are terms (main topics) represented by their label and, by default, a circle.

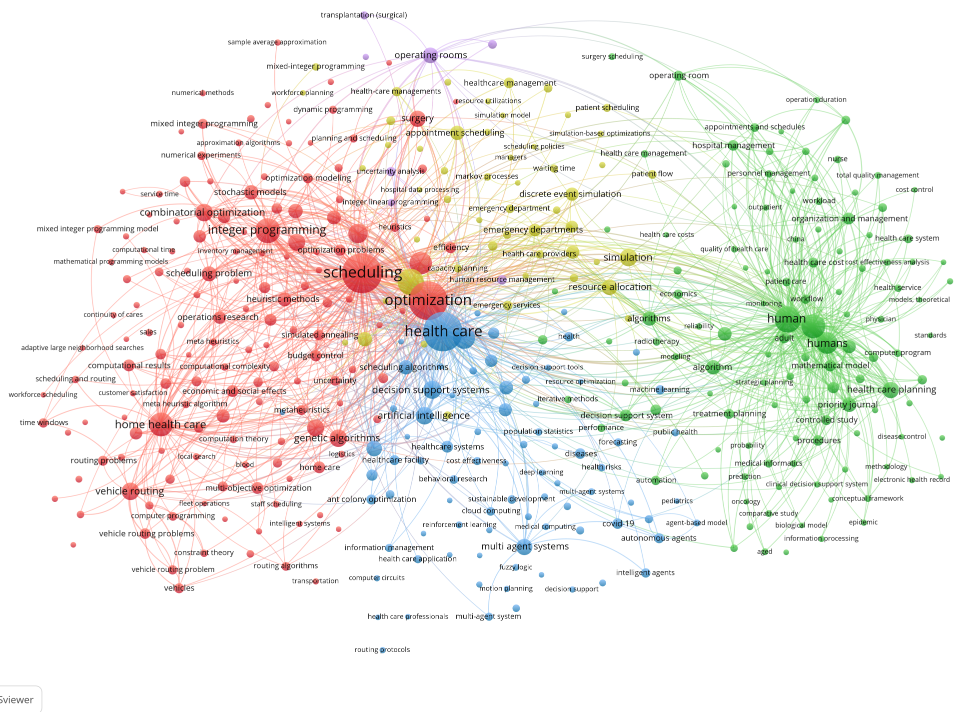

Figure 61: Co-occurrence keywords.

The size of the label and the circle of a term is determined by the weight of the term. The higher the weight of a term, the larger the label and the circle of the term. For example, the main terms are scheduling, optimization, and healthcare. The color of a term is determined by the cluster to which the term belongs. In Figure 61 it is possible to identify the different clusters, which cluster complementary or more related terms by different colors, for example, in the cluster in blue, we have topics more related to AI, MAS, decision support, information management, among others. In turn, the lines between the terms represent links.

On the other hand, Figure 62 represents the co-occurrence of the keywords but with an overlay view. The overlay visualization is identical to the network visualization except that items are colored differently. There are two ways in which items can be colored in the overlay visualization. If items have scores, the color of an item is determined by the age parameter, where by default colors range from blue (older) to green to yellow (more recent).

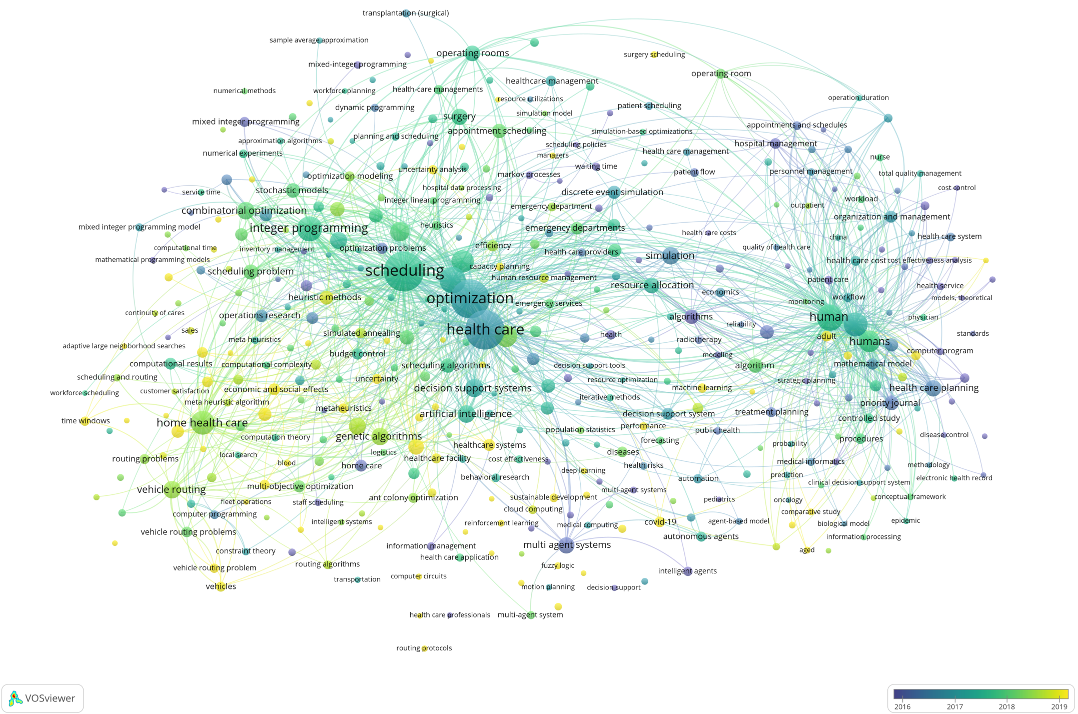

Figure 62: Co-occurance keyworkds with overlay visualization.

In Figure 62 a color bar is shown in the bottom right corner of the visualization. The color bar is shown only if the colors are determined by the age parameter of the items. The color bar indicates how the scores are assigned to the colors. It is interesting to see the recent impact of terms such as “healthcare facility”, “customer satisfaction”, “uncertainty analysis”, “machine learning”, “covid-19”, among others.

Another knowledge structure according to the database, namely a conceptual structure, represents the relationships among concepts or words in a set of publications. Similarly to network analysis, factorial analysis (data reduction techniques) is helpful in identifying sub-fields. Various dimensionality reduction techniques can be applied, such as correspondence analysis (CA), multiple correspondence analysis (MCA), multidimensional scaling (MDS), and principal component analysis (MCA). Clustering algorithms can be used in both cases of network or factorial analysis. Thus, Figure 63 presents a correspondence analysis and clustering using a dendrogram of words.

Taking into account Figure 63, the height measures the distance among words or clusters of words. The height helps to choose where to cut the dendrogram defining the partition. “Similar words” explain a similar “concept”

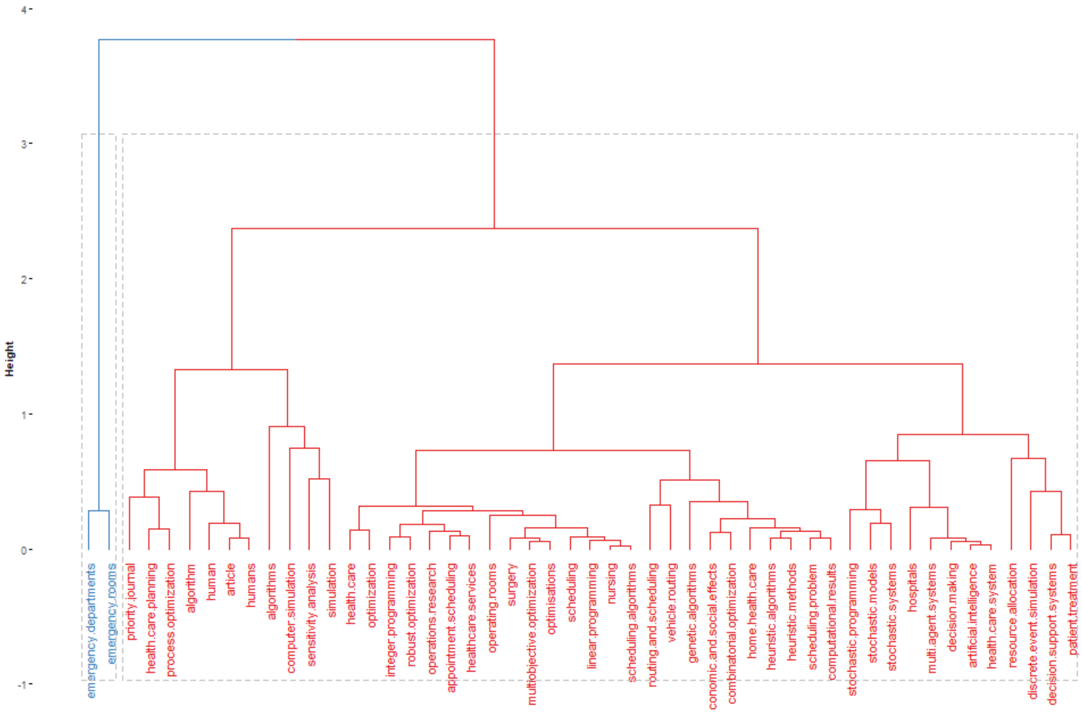

Figure 63: Factorial analysis based on topic dendrogram.

or topic, and "distance words" define a different "concept". In this case, we have two large clusters (automatically generated) that only differentiate the emergency words from the others, mainly because these are more reactive issues and unexpected events that are still not widely considered nowadays.

Finally, and as a summary, the comparison between keywords plus and authors keywords, by occurrence, will be presented in Figure 64. Keywords plus are terms able to capture and article content with greater depth and variety. Furthermore, keyword plus is as effective as author keywords in terms of bibliometric analysis investigating the knowledge structure of scientific fields. These words are extracted by titles (or abstracts), and some abstract words need to be cleaned by trivial terms such as "paper", "study", "word", "data". among others.

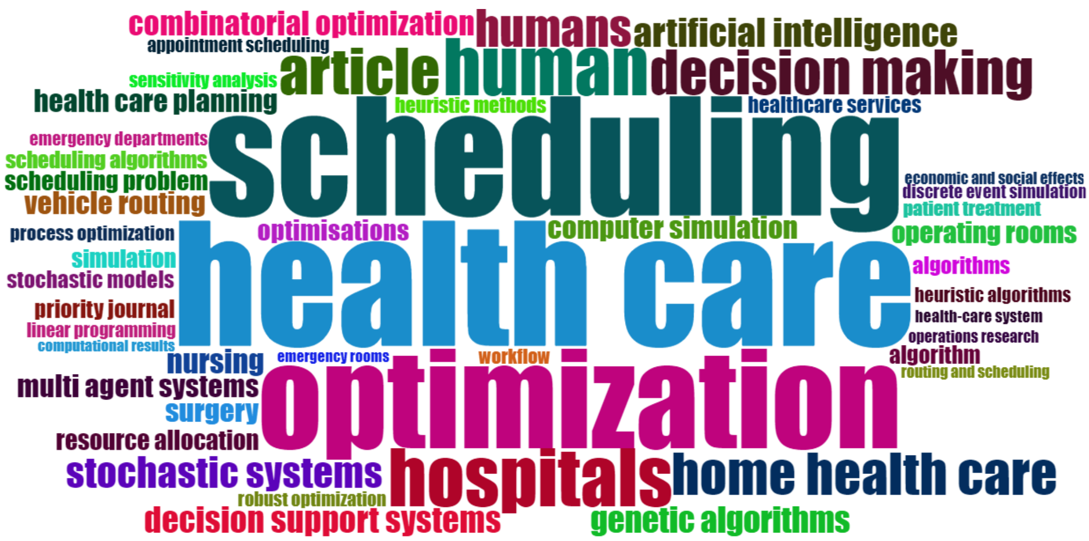

Figure 64: Wordcloud based on keywords plus.

As represented in Figure 64, the top keywords plus are represented by a word cloud. A tag cloud (word cloud, or weighted list in visual design) is a visual representation of text data, typically used to depict keyword metadata (tags) or to visualize free form text. Tags are usually single words, and the importance of each tag is shown by font size or color. This type of graph is useful for quickly perceiving the most prominent terms and for locating a term alphabetically to determine its relative prominence. In the previous figure it is clear to see which words are most prominent (by color and size), at the same time, it allows one to identify some that are distributed and related to the others (it can be highlighted, for example, "stochastic systems", "robust optimization", "decision support systems", "artificial intelligence", among others).

In summary, this appendix allowed a broader notion of the bibliometric analysis carried out, its methodology, tools and some of the results, which can be used as an indication of the importance and impact of the work or that of a research group, department or university, and therefore of its value to the wider research community.

C

Details about the Database Module and Technologies used in the DOCtoR Specification

DOCtoR's success has been built on many details, ranging from strategy, analysis and planning, design, application development, testing and deployment.

With respect to the construction of the database module, SQLite was used. SQLite is an in-process library that implements a self-contained, serverless, zero-configuration, transactional structured query language (SQL) database engine. The code for SQLite is in the public domain and is thus free for use for any purpose, commercial or private. SQLite is the most widely deployed database in the world with more applications than we can count, including several high-profile projects [111]. One of SQLite's greatest advantages is that it can run nearly anywhere. SQLite has been ported to a wide variety of platforms: Windows, MacOS, Linux, iOS, Android, and more.

Taking into account the necessary database, the DOCtoR platform seeks to generate a database file that generated an SQLite entity relationship diagram (Figure 65). In this sense, multiple tables were created which are linked to each other through a relationship. A relationship is where you have multiple tables that contain related data and the data are linked by a common value stored in both tables. Thus, for example, the depot (health center or IPSS) has a number of vehicles, patients, care workers, routes and managers related to it.

This entity-relationship model is a visual representation of the table's structure and the relationships between logically related tables. In this type of modeling the database structure is represented as a diagram known as an entity-relationship diagram. Thus, it is possible to obtain a better understanding of the overall DOCtoR database structure. It should be noted that the agent optimization results tables are not linked due to the fact that at the initial time, the platform was in testing and at that time the diagram was still in a preliminary version. However, as we are dealing with a prototype with the potential for real implementation and diversification across multiple sectors of society, this work does not present the most up-to-date version of the database.

On the other hand, it is interesting in this appendix to indicate the set of tools and technologies used for the design and development of the DOCtoR prototype. These tools and technologies allowed and still allow the quality of planning and innovation, software analysis, architecture and design and project management. In terms of tools (and database) considered for developing the interfaces, the following were used:

- Visual Studio 2020;
- .NetCore SDK;

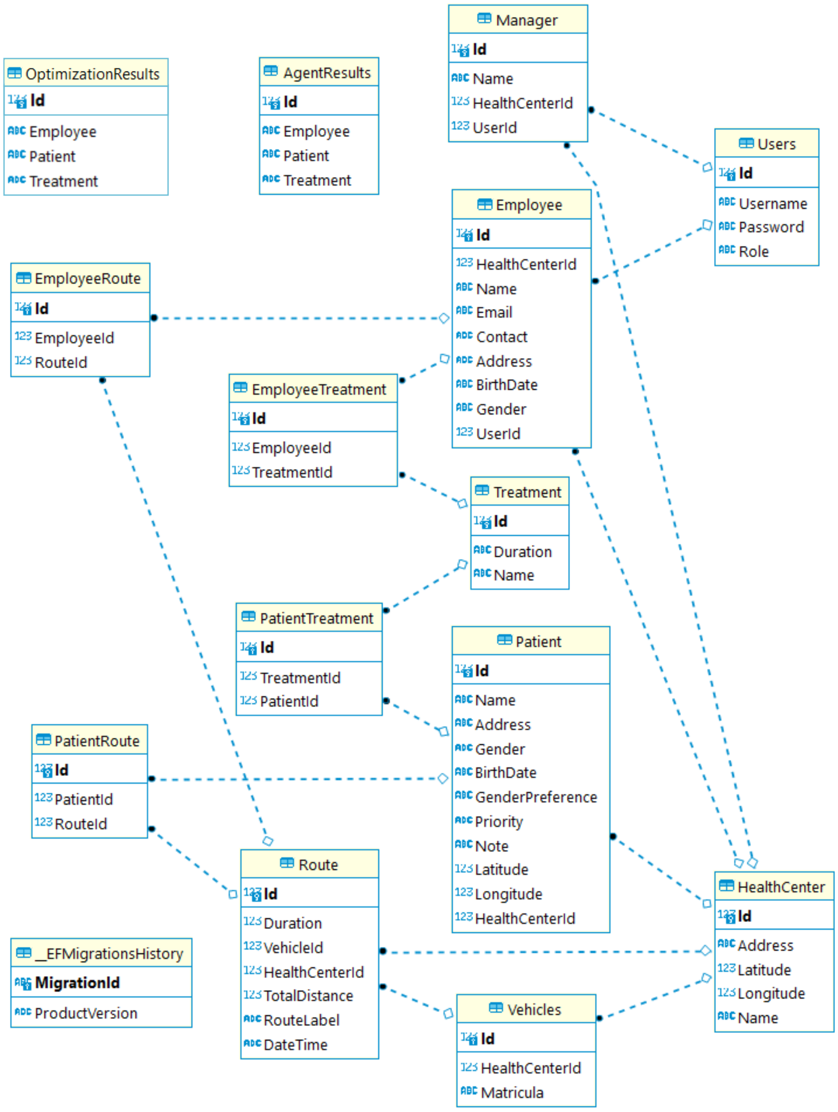

Figure 65: DOCtoR database entity-relationship diagram.

- Intellij 2020;
- Git/Source Tree;
- SQL Server/SQLite Studio;
- Postman;
- Azure;
- Gitlab;
- MatLab;
- Trello;
- React Native;

In terms of technologies or programming languages, the following were used:

- Git;
- .NetCore 3.1/5;
- c#;
- Razor Pages;
- HTML/CSS/JavaScript;
- SQL/SQLite/SLQServer;
- Entity Framework;
- .NetCore Identity Framework;
- REST API;
- JWT Authentication/Authorization;
- Kotlin/Java;
- Micronaut;
- JADE - MAS;
- Google OR-Tools;
- TCP/IP;
- React;
- Angular.

All of these tools and technologies were aimed at data management, route visualization, scheduling visualization, live route tracking, role-based authentication, and the design/implementation of appealing layouts. The integrated modules also benefited from the use of many of these technologies, from the API, database, optimization module and MAS module. These modules were always adjusted according to the "rules" of the final product, with maintenance capabilities and improvements over time.

During development, for example of the web application, wireframes/sketches of new/existing layouts were analyzed and designed. The implementation resorted to HTML, CSS, JavaScript and Razor Pages following the Model-View-ViewModel (MVVM) pattern. Several adjustments were also made to the API according to the needs defined for the user interface (filters, searches, among others). The work plan also considered manipulating the data in the relational database, according to the imposed needs. Regarding security, authentication and authorization aspects, different roles and authorizations were planned for the different users. In addition, rules were implemented using the respective framework (identity provider). However, the limitation of visualization according to "business" rules is still being studied. In the future, some extras may be studied for inclusion in DOCtoR, namely in terms of real-time, with the integration of SignalR technology in the defined architecture.