Chapter 1
Introduction

In an era characterized by rapid advancements in healthcare and an aging population, the need for efficient and accessible healthcare solutions has never been more apparent. This fact was laid bare during the recent COVID-19 pandemic. On the one hand, where we were able to successfully develop the vaccines in record time, almost seven million people died due to the pandemic. In the case of India, with half a million COVID-19-related deaths, it was clear that a rapid improvement in the healthcare infrastructure was required. In response, the Healthcare Federation of India produced a white paper titled '*Indian Home Healthcare 2.0: Redefining the Modern Care Continuum'* (NATHEALTH, 2021). The document highlights the benefits of a sufficiently developed home healthcare sector in providing a viable alternative to traditional healthcare services. In the modern healthcare landscape, home healthcare systems can offer a plethora of benefits to patients and their families. These innovative systems empower individuals to receive high-quality medical care within the comfort and familiarity of their own homes, alleviating the burden of frequent hospital visits and promoting a more independent and dignified lifestyle. With a focus on personalized care, convenience, and improved patient outcomes, home healthcare systems represent a transformative approach to healthcare delivery that is essential and advantageous in today's healthcare landscape.

The benefits of home healthcare services have been observed in recent years. The pandemic caused by the COVID-19 virus has impacted every aspect of our lives and resulted in an unprecedented crisis all over the globe. To control the spread

of COVID-19, limiting the gathering of a large number of people at a single place and restricting inter-personnel contacts are considered the most primary and effective ways by the World Health Organization (WHO, 2020) As a response to this, several businesses have adopted the strategy of providing the services to the doorstep of the customers instead of the conventional way of customers visiting the service-providing facilities (OECD, 2020). The healthcare sector is no exception to this. Traditional healthcare facilities such as primary healthcare centers, nursing homes, hospitals, and pathology centers can be at a higher risk of spreading the virus due to the gathering of sick and vulnerable people at these locations. On the other hand, 'unconventional' healthcare services such as telemedicine and home healthcare services (decentralized healthcare services) can prove to be quite effective in achieving the goal of limiting unnecessary contacts (NCIRD, 2020). While telemedicine is suitable for remote consultation, home healthcare has an additional advantage of in-person engagement that might be essential for delivering some of the services. Additionally, home healthcare also has the potential to prevent the unnecessary movement of sick (most vulnerable) and infected (most contagious) individuals by reducing the requirement for normal hospital visits. In an emergency like the COVID-19 pandemic, a home healthcare system can also help reduce the burden from traditional healthcare institutes and allow them to tackle the ever-evolving situation with more agility.

1.1. About the Home healthcare delivery

In general, Home HealthCare (HHC) delivery involves the operation of delivering a wide variety of healthcare products and services to a patient's home. First, the requests regarding the patient's needs are collected. Then, based on the available capacity, the healthcare provider tries to fulfill the demand while

maximizing the organization's stated goal. **Figure 1.1** presents an example of a general home healthcare setup, where multiple staff can be dispatched from more than one location to meet a patient's unique combination of requests.

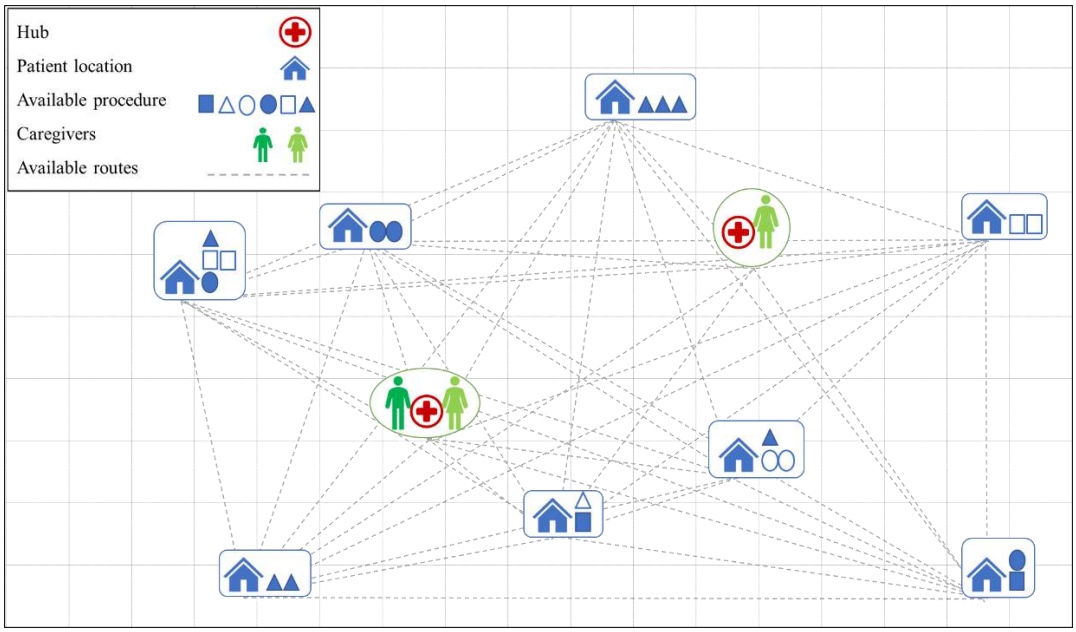

Figure 1.1: Diagram of a home healthcare delivery setup.

In recent times, home healthcare delivery has become an essential aspect of modern healthcare systems, providing medical and non-medical services to individuals in the comfort of their own homes. In addition to the benefits of home healthcare services during a pandemic, it can offer numerous advantages, like improved patient outcomes, reduced healthcare costs, and enhanced patient satisfaction. However, delivering healthcare services in a home setting comes with a myriad of complexities that pose unique challenges for healthcare providers, patients, and the overall healthcare system. Some of the critical considerations are patient-caregiver coordination, regulatory issues, workforce challenges, and ethical considerations. Unlike traditional hospitals where care teams are centralized, home healthcare requires seamless collaboration among various healthcare professionals,

patients, and their families. Coordinating care across multiple providers, managing patient appointments, and ensuring timely communication are some of the critical challenges. Moreover, home healthcare often involves patients with complex medical and personal conditions, requiring the integration of diverse medical specialties, therapies, and equipment.

1.2. Research Motivation

It should be noted that HHC services existed before the recent COVID-19 pandemic. It is, in fact, well-established in most of the developed countries and is on the verge of expanding in developing countries such as India. According to the Managing Director and Chief Executive Officer of Portea Medical (one of the largest Indian HHC delivery services), in comparison to countries like the USA, where home healthcare comprises 8.3% of the $280-billion healthcare industry, India falls behind severely comprising merely 2% of the spend (Meena Ganesh, 2018). However, the rate of growth in India is much higher. The Indian home healthcare market was expected to grow to around $4.46 billion by 2018 and $6.21 billion by 2020 (CMR, 2016). This prediction was backed up by the Grand View Research report published in June 2020. According to it, India's HHC market was valued at USD 5.2 billion in 2019 and is projected to expand at a compound annual growth rate (CAGR) of 19.2% from 2020 to 2027 (GVR, 2020). This was further updated to 19.29% for 2023-30 in 2023, with the value of the Indian home healthcare market estimated at USD 8.8 billion (GVR, 2023). To put this in context, the global home healthcare market was projected to reach $364.69 billion by 2022 from $220.76 billion in 2016, registering a CAGR of only 8.8%. The adoption of home healthcare solutions in India is thus clearly at its early stage.

Further, In India, the elderly population (above 60 age group) is growing faster than the overall population growth. It is expected to move from 8% of the total population in 2015 to 19% by 2050 (Meena Ganesh, 2018). This, combined with the increasing incidence of chronic diseases, affordability and awareness, high levels of stress, and lack of work-life balance, will become some of the key factors that necessitate the development and promotion of the Indian home healthcare sector in the near future. A report by Cyber-Media Research revealed that home healthcare has the potential to replace up to 65% of unnecessary hospital visits in India and reduce hospital costs by 20% (CMR, 2016). For Example, the daily expenses for staying in an ICU at a hospital range from USD 450 to USD 650, whereas establishing an ICU facility at home, including equipment and medical expertise, can cost between USD 95 and USD 125 per day.

The untapped potential of the home healthcare sector has also been acknowledged by the government of India. The Indian government has recently launched initiatives to promote the rapid development of home healthcare services in India. As mentioned earlier, the Healthcare Federation of India released guidelines titled *'Indian Home Healthcare 2.0'* in January 2022, which incorporated the perspectives from industry stakeholders alongside the government recommendations for creating significant growth opportunities for home healthcare services in India (NATHEALTH, 2021). Although there are few works that address a variety of challenges associated with HHC services, there is a paucity of contributions related to the challenging problem of routing and scheduling the home healthcare staff in the Indian context. This clearly highlights the significance and need for thorough research in the HHC delivery field in India. The present thesis tries to fill this gap.

1.3.Research issues

The following issues must be addressed in order to develop a widely acceptable OR-based decision support system for the Indian home healthcare industry.

i. As healthcare services are provided by various types of organizations, such as government, private sector, and non-profit organizations, their goals can vary significantly. Additionally, a specific organization can simultaneously have more than one goal, which needs to be accounted for in the model. Further, the relative priorities of goals can change with the organization and its developmental phase. Effective strategies need to be developed to capture these scenarios.

ii. It has been observed that there is a lack of adoption of OR methodology in the HHC industry. This should be a significant consideration while developing new mathematical models and solution approaches. This issue is particularly relevant in developing and underdeveloped countries, despite the extensive research being conducted on OR-based techniques to enhance home healthcare delivery.

iii. Besides the number of procedures being offered, the nature of the procedure itself needs to be considered. Some procedures may require multiple staff and/or multiple visits in a day. Additionally, a combination of procedures may have precedence or disjunction criteria, which will influence their sequence and a minimum time gap. This issue should be addressed while developing the model to achieve a wider acceptability.

iv. There are several cultural and socio-economic aspects that influence the HHC services in India. Alongside patient's demand for the required

procedures, their preferences regarding time and staff compatibility are needed to be taken into account. Owing to the linguistic diversity of the country, where 22 different languages are recognized in the Indian constitution itself, the language compatibility for both HHC staff (caregivers) and patients' needs to be considered for the assignment. Similarly, due to the prominence of conservative culture in Indian society, patients' preference regarding the gender of caregivers is also an important dimension. These factors, although they seem to be more prevalent in the Indian setting, can also be considered for a generic setting.

v. Social issues need to be at the forefront while designing a system for long-term sustainability. In the case of home healthcare delivery, issues relating to the fair workload distribution among caregivers, job assignments to better suit the qualifications, and general considerations during the daily operations of the organization need to be included.

vi. The nature of the time-window (hard or soft) associated with patients' services also needs to be considered. Often, a single preferable time window for the patient is only considered in the existing literature. However, including multiple preferable time windows and/or an 'Inconvenient time window' (ITW: the intervals to be avoided while scheduling a procedure) can lead to higher acceptability of home healthcare services in fringe cases and need to be explored.

vii. For an overburdened healthcare system, a typical state for an Indian healthcare provider, criteria for the selection and the rejection of patient/procedure request needs to be explored. A service provider may reject a patient if they are not capable of meeting the patient's demand in

full. However, loss of business due to rejected patients motivates the exploration of a partial demand fulfillment policy.

viii. A more intricate HHC delivery model needs to be developed to enhance the capability of the existing setup. Effect of 'Inconvenient time window' (ITW) on task scheduling, proper scheduling of multiple tasks in the absence of a convenient time window, and strategies to limit the spread of a contingent (like the COVID-19 virus) has been identified as the potential avenue for exploration.

ix. Incorporation of all the above-mentioned complexity in a single monolithic mathematic model has proven to be a challenging endeavor. In addition to developing such a model, solution techniques needed to find meaningful results for a real-world instance can easily surpass the average available computational budget. To find the workable balance, a general trend in the literature has been to develop a case-specific model that can be solved quickly.

1.4. Research objectives and scope of the thesis

Motivated by the economic opportunity as well as the need for the development of HHC services in India and its immense inherent complexity, we consider the home healthcare delivery problem as an integrated routing and scheduling problem with multiple hubs consisting of the heterogeneous workforce and propose a generic single-period mixed-integer programming model that can easily be adapted for a variety of HHC setup without any need for significant modifications. The proposed MIP model should incorporate most of the commonly used restrictions/complications from the existing literature in the HHC field (such as various procedures' characteristics, their interdependencies, and patient-

caregiver compatibilities, etc.) and produce the request-to-caregiver assignment, sequence and the schedule for the assigned visits to each caregiver. Additionally, based on the research gap identified from the existing literature, further refinement for the HHC problem can be proposed in a couple of areas. The model can be enhanced to incorporate the restriction on unnecessary interaction between individuals, which can prove to be quite helpful in case of a viral outbreak. Similarly, while scheduling multiple visits to a single patient, it is essential to avoid unnecessary spread-out visits to improve service experience. Methods to incorporate these into the decision-making process should be explored. Finally, it can be said that the HHC organizations in various stages of maturity and with varying financial incentives will have widely different goals from one another. A single and rigid objective function cannot be expected to meet the goals of different healthcare facilities. It will undoubtedly lead to hesitation from the management in adopting the proposed MIP model. To accommodate these variations, the monolithic MIP model is further developed to incorporate multi-objective decision-making and provides a set of well-diverse Pareto solutions for the decision-maker's consideration. In summary, the objectives of the research can be described as follows.

i. Develop a monolithic home healthcare delivery model and solution methods to produce routing and scheduling decisions for a healthcare facility that employs a set of heterogeneous staff. The staff may need to be deployed from multiple hubs based on deterministic demand, patient preferences, caregiver qualifications, various procedure characteristics, and interdependencies. The models should also include the two request accommodation policies.

ii. Design and formulate a multi-objective home healthcare delivery model with solution techniques capable of producing a diverse set of Pareto solutions in order to incorporate multiple goals of major stakeholders from a home healthcare delivery organization. The organization is assumed to employ a set of heterogeneous staff that can be deployed from various hubs under the deterministic demand, patient preference, caregiver qualifications, and procedure characteristics and interdependencies.

iii. To introduce the following capabilities to the HHC literature:

   a. Introduce the methodology to limit the person-to-person interaction during the daily delivery of home healthcare services. The model should be able to track every interaction between individuals and should restrict any additional assignments that violate the prescribed exposer limit.

   b. Introduce the 'Inconvenient time window' as a concept in home healthcare delivery literature and incorporate its variations in the proposed HHC model.

   c. Introduce and define the 'patient's inconvenience' caused by improper scheduling when organizing multiple visits in a single day. Additionally, establish the relation between 'Patients' inconvenience' and 'Net profit' for a generalized home healthcare delivery setup.

The scope of the thesis is limited to studying a single-period home healthcare delivery problem under a highly generalized setup. The HHC problem is formulated and analyzed under a deterministic environment. Patients' attributes and demands, alongside caregivers' capabilities and availabilities, are known in

advance. We consider a diverse set of caregivers classified by their gender, language fluency, procedure capability/proficiency level, and nature of employment. It is assumed that caregivers can be deployed from multiple hubs in two partially overlapping shifts. Further, we do not put any limitation on the nature of procedures. Models are designed to accommodate procedures that simultaneously require multiple staff as well as multiple visits in a single day while adhering to their precedence requirements. Working regulations are handled by including a mandatory break, a limit on the daily workload of staff, and overtime payment. We do not consider any aspect of caregivers' travel arrangements. It is assumed that caregivers will complete their assigned routes by any means necessary, where travel cost is proportional to the travel time. Finally, Problem instances and analysis mainly focus on an overburdened healthcare facility, where assignment, routing, and scheduling decisions are to be made to improve the organization's service level while fulfilling the abovementioned requirements. Within the described home healthcare (HHC) setup, the current study aims to address the following research questions:

i. What is the most efficient method for solving large-scale home healthcare delivery problems?
ii. What is the most effective 'request accommodation policy' when the HHC service provider must balance revenue and service level?
iii. Should the HHC service provider hire additional staff to meet the increased demand?
iv. How do efforts to reduce 'patient inconvenience' impact the net profit?
v. Is it possible to significantly reduce patient inconvenience without sacrificing net profit?

1.5.Outline of the thesis

The remainder of the thesis is organized as follows. Firstly, a review of relevant literature is presented in Chapter 2. The home healthcare delivery problem is placed into the wider routing and scheduling problem by citing the relevant and current research work. Particular focus is provided to the various aspects of home healthcare delivery, such as considered objectives, relevant constraints, and length of the planning horizon. Considered literature also includes the multi-objective setup of home healthcare delivery problems along with the techniques to handle multiple objectives. Finally, solution methodologies such as exact, heuristics, and metaheuristics are discussed. The literature review further establishes the research gap in the field of home healthcare delivery and concludes with a summary of proposed enhancements to the area.

Chapter 3 presents a generalized model for the integrated problem of routing and scheduling of the home healthcare delivery staff (caregivers) to maximize the revenue generated. As previously outlined, the model is designed to consider most of the commonly used constraints from the extant literature and specific concerns such as patient's preferences for the gender and language of the caregiver, inconveniences time window, and multiple visits for specific procedures that are motivated from the case of an Indian home healthcare service provider. The model is capable of handling multiple visits as well as multiple staff requirements for procedures in order to generate proper assignments, schedules, breaks, and routes. A unique prospect of the model is the consideration of limited person-to-person contact to minimize the risk of exposure. The model tries to serve the maximum number of patients fully without violating a predetermined maximum allowed contact limit for every patient as well as healthcare staff. Additional policy

decisions of allowing partial satisfaction of patient request to maximize resource utilization and the financial viability of hiring additional capacity to fulfill all the demand are also tested. To solve the proposed mathematical model, three decomposition-based matheuristics (math-heuristics) alongside a novel implementation of a Genetic algorithm, called p-GA, that utilizes inherent parallelism in the evolutionary process are presented. Experiments are conducted to find the most efficient algorithm for small, medium, and large-size problem instances. The validity of the generalized mathematical model is then demonstrated by solving and analyzing a famous benchmark instance from the literature. The performance of four considered objective functions is compared using a normalized utility score. The most appropriate choice for the same, which will produce the least compromise on other criteria, is declared. Finally, the resource requirement to achieve complete demand satisfaction is ascertained by utilizing the generalized mathematical model, and insight is presented with regard to the right strategy for hiring full-time/part-time staff.

Chapter 4 presents a mixed-integer programming model for a multi-objective home healthcare delivery problem. Similar to the previous chapter, the multi-objective problem is also modeled with minimum assumptions about the procedure attributes and can handle most of the commonly imposed restrictions in the field of home healthcare delivery. Under the imposed conditions, the model is designed to provide selection (for caregivers and patients), assignment, scheduling, and routing decisions. In addition to minor modifications in ‘workload balance’ constraints, a major focus of the work is to improve the quality of the schedule for the selected patients. To achieve this, we define and calculate the inconvenience caused by the unnecessarily scattered visits and their overlap with the patient-

specific inconvenient time window. The model minimizes the total inconvenience cost for patients against the competitive goals of other stakeholders. Higher net profit, minimum loss of employed labor, balanced workload among staff, and maximization of fully served patients have been included as the other objectives. To solve the instances of the proposed home healthcare delivery problem, an efficient implementation for a reference point-based non-dominated sorting genetic algorithm (NSGA-III) is developed. After extensive parameter tuning using the Taguchi method of experimental design, the algorithm is used for generating a diverse set of non-dominated solutions for the decision-maker. In addition to comparing the performance of NGSA-III with Multi-objective particle swarm optimization and Multi-objective grey wolf optimizer, experiments are also carried out to establish the relationship between patient convenience and net profit.

In Chapter 5, we conclude the work by summarizing the main contributions of the thesis. Further, future research directions are presented following the key managerial insights.