Models and Algorithms to Facilitate the Logistics Operations of Caregivers for Home Healthcare Services in India

Thesis submitted towards the partial fulfillment

for the Award of Degree

Doctor of Philosophy

By

Niteesh Yadav

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY

(BANARAS HINDU UNIVERSITY)

VARANASI-221005

INDIA

19101002 **2023**

CERTIFICATE

It is certified that the work contained in the thesis titled **“Models and Algorithms to Facilitate the Logistics Operations of Caregivers for Home Healthcare Services in India"** has been carried out by **Mr. Niteesh Yadav** and that this thesis has not been submitted elsewhere for a degree or a research proposal.

It is further certified that the student has satisfactorily fulfilled all the requirements of the Comprehensive Examination, Candidacy, SOTA, Pre-submission seminar for the award of the Ph.D. degree.

Dr. Saurabh Pratap
(Program Coordinator)

Assistant Professor
Department of Mechanical Engineering
IIT (BHU), Varansai-221005

DECLARATION BY THE CANDIDATE

I, **Niteesh Yadav,** certify that the work embodied in this thesis is my own bona fide work and was carried out by me, from July 2019 to October 2023, at the Department of Mechanical Engineering (Industrial Management), Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, thesis, etc., or available at websites and have not included them in this thesis and have not cited as my own work. **I further declare the that I will be solely responsible for any plagiarism if found at a later stage.**

Date: 20 November 2023

Place: IIT (BHU) Varanasi, India

(NITEESH YADAV)

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of my/our knowledge.

Dr. Saurabh Pratap
Assistant Professor
Department of Mechanical Engineering
Indian Institute of Technology (BHU), Varansai-221005

Dr. Saurabh Pratap
Assistant Professor
Department of Mechanical Engineer.
Indian Institute Technology (BHU)
Varanasi-221005, India

Prof. Santosh Kumar (The Head)
Department of Mechanical Engineering
Indian Institute of Technology (BHU), Varanasi-221005

विभागाध्यक्ष/HEAD
यान्त्रिक अभियान्त्रिकी विभाग/Deptt. of Mechanical Engg.
भारतीय प्रौद्योगिकी संस्थान/Indian Institute of Technology
(का०हि०वि०/B.H.U.)
वाराणसी-२२१००५/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis:	Models and Algorithms to Facilitate the Logistic Operation of Caregivers for Home Healthcare Services in India
Name of the Student:	Niteesh Yadav

Copyright Transfer

The undersigned hereby assigns to the Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of ***DOCTOR OF PHILOSOPHY.***

Date: 20 November 2023

Place: IIT (BHU) Varanasi, India

(NITEESH YADAV)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisor**, Dr. Saurabh Pratap**, for his guidance and support throughout my stay at this institute. I also thank him for accepting the position of my program coordinator when I needed it most. While I did not get enough time to benefit fully from his experiences, I am fully aware that without his intervention and support, it would have been impossible for me to complete my PhD degree. I extend my sincere gratitude to **Dr. Ajinkya Tanksale** for his guidance. He has shown an infectious enthusiasm and extraordinary patience for every half-baked idea I brought to him. He is an inspiration to me as a researcher and scholar, exemplifying what it means to be a good human being. For all of this, I shall be forever grateful to him. Again, I wholeheartedly thank both of them for their care and counseling and look forward to further benefiting from their knowledge and wisdom in the coming years.

I also thank **Prof. A.K. Agrawal, Prof. Prabhas Bharadwaj, Dr. Cherian Samuel,** and **Dr. Lakshay** for their guidance and continuous motivation. Together, they represent an institute of knowledge that any research scholar would be privileged to witness and is advised to make full use of. I also thank **Dr. Debdas Ghosh, Dr. Lakshay,** and **Dr. Ravi Panwar** for providing valuable and constructive comments as members of my research progress evaluation committee (RPEC). I thank all of them for advising me throughout my research and the completion of this thesis. I also extend my sincere thanks to **Prof. Santosh Kumar**, Head, Department of Mechanical Engineering, IIT (BHU) Varanasi, for providing me with the necessary resources to complete this research work. Additionally, I would like to express my gratitude to the Department of Mechanical Engineering and its staff for providing me with the necessary facilities to conduct my research work smoothly. I also formally acknowledge the support and resources provided by the ‘PARAM Shivay facility’ established under the Indian Government’s National Supercomputing Mission.

During this research journey, I have met many people who have made this period of my life memorable and very pleasant. Among them, I would like to especially acknowledge the support and assistance provided by Dr. Anubha Rautela, Mr. Meghavatu Krishna Naik, and Dr. Ajeet Kumar Yadav in the pursuance of my PhD degree. I also thank Dr. Susheel Yadav, Dr. Amit Amber Gupta, Dr. Rishi Ram, Dr. Priya Singh, and Dr. Ankit Chouskey for helping me through the day-to-day issues of the research work whenever needed. I sincerely thank all of them from the bottom of my heart for their support.

Finally, I would like to acknowledge the unrepayable contribution of my family in achieving the successful completion of this thesis. I offer my deepest love and respect to my beloved parents, Mr. Nandlal Yadav and Mrs. Kiran Yadav, knowing that any word of thanks will be unbelievably incapable of expressing my gratitude. Their everlasting encouragement, patience, sacrifice, and blessings have brought me to this stage. I also express my deepest and sincere appreciation to my loving sisters, Dr. Niharika Yadav and Dr. Nidarshana Yadav, for their unwavering support and encouragement. My family is my continuous inspiration and my biggest supporter, and none of this would be possible without them. In the end, I humbly bow my head before the almighty Lord Shiva for his blessings.

Niteesh yadav

Date: 20 November 2023

Place: IIT (BHU) Varanasi, India **(NITEESH YADAV)**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

WHO	World Health Organization
OECD	Organisation for Economic Co-operation and Development
NCIRD	National Center for Immunization and Respiratory Diseases
HHC	Home HealthCare
GVR	Grand View Research
CAGR	Compound Annual Growth Rate
USD	United States Dollar
ITW	Inconvenient Time Window
MIP	Mixed Integer Program
NSGA	Non-dominated Sorting Genetic Algorithm
HHCRSP	Home HealthCare Routing and Scheduling Problem
VRP	Vehicle Routing Problem
TOP	Team Orienteering Problem
VRPTW	Vehicle Routing Problem with Time Window
MOWFA	Multi-Objective Water Flow-like Algorithm
MOSA	Multi-Objective Simulated Annealing
MOICA	Multi-Objective Imperialist Competitive Algorithm
GPU	Graphics Processing Unit
p-GA	Parallel-processed Genetic Algorithm
MD-HVRPTW	Multi-Depot Heterogeneous Fleet Vehicle Routing Problem with Time Windows
SSD	Single Stage Decomposition
MSD	Multi-Stage Decomposition

LS	Local Search
GA	Genetic Algorithm
QS	Quality Score
MAL	Maximum Assignment Limit
RDH	Rank-based Decomposition Heuristic
CV	Capability Value
AV	Accessibility Value
TFLOPS	Trillion Floating Point Operations Per Second
ANOVA	Analysis of Variance
MOPSO	Multi-Objective Particle Swarm Optimization
MOGWO	Multi-Objective Grey Wolf Optimizer
PSO	Particle Swarm Optimization
POD	Point-of-difference
PFA	Pareto Front Approximation
MID	Mean Ideal Distance
SNS	Spread of Non-dominated Solution
MS	Max-spread
DOE	Design of experiment

PREFACE

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'*. The document highlighted the benefits of a sufficiently developed home healthcare sector in providing a viable alternative to traditional healthcare services. Hence, in the current work, we aim to design and develop OR techniques to facilitate the logistics operations of home healthcare delivery, an essential part of home healthcare services. Simultaneously, we intend to provide robust solution methodologies that can be used for a wide variety of home healthcare delivery setups.

In this thesis, we consider a single-period home healthcare delivery problem, where a heterogeneous set of caregivers are to be deployed from multiple hubs to fulfill the demands of multiple patients. The thesis focuses on developing methodologies that can be useful for as many home healthcare delivery services as possible without much friction. This translates into the development of generalized home healthcare delivery models alongside efficient and robust solution approaches. Further, the selection of the objective function needs to be done very carefully. With the competitive goals of the different stakeholders and the varying maturity levels of various home healthcare delivery organizations, any generalized model should be designed to accommodate obscure combinations of objective functions. Finally, the gaps in the existing literature on the home healthcare delivery problem regarding the more refined scheduling, multiple time windows, and contact restriction methods need to be filled. To capture these research themes, three broad sets of objectives are defined.

In the first objective, a mathematical model that can be used to represent a wide variety of home healthcare delivery setups is developed. Patients' demands are modeled in a general fashion, with as many attributes as possible. The mathematical model also incorporates the most commonly appearing constraints from the home healthcare delivery literature. Developed models can be reduced to represent more obscure scenarios by strategically omitting certain constraints or altering parameter values. The resulting monolithic home healthcare delivery model is tested on a benchmark problem set, and a method for adapting the mathematical model to the benchmark problem is provided. The modified model is found to be capable of solving the benchmark problem for 26 out of 30 instances. Two MIP-based matheuristic, namely single-stage decomposition (SSD) and multi-stage decomposition, alongside the parallelly processed version of the genetic algorithm (*p*-GA), are developed. Statistical analysis is carried out to establish the appropriate niche for each algorithm. Finally, *p*-GA was used to find the favorable combination of objective function and 'demand satisfaction policy' for an overburdened healthcare system. In the second objective, we extend the monolithic mixed integer programming model to a multi-objective setup. The multi-objective variant of the model is developed to accommodate the competitive goals of the different stakeholders from a home healthcare delivery setup. Twelve criteria are initially identified for optimization. These criteria are eventually categorized into five objective functions based on the requirements of three stakeholders (patient, caregivers, and management). Multi-objective metaheuristics like NSGA-III, MOPSO, and MOGWO are used to produce diverse Pareto solutions. NSGA-III with single point crossover operator is found to be the most efficient for solving the multi-objective home healthcare delivery problem. The Pareto set obtained from the same is also tested for the 50% variation in service time and travel time. Approximate Pareto front is found to be robust, with only 11% to 17% maximum degradation in key quality indicators.

Further, as the third objective, the thesis adds novelties to the home healthcare delivery problem. First, an extensive literature review identifies some gaps in the existing literature. Constraints to restrict unnecessary contact between patients and staff have been added to the monolithic mathematical model. 'Contact restriction' constraints use a prescribed maximum number of allowed contacts as a hard limit for each entity. Similarly, models incorporate the 'inconvenient time window' as an example of multiple favorable time windows where a visit can only be scheduled into one of the time slots. The thesis also presents a soft implementation of the 'inconvenient time window' constraints by allowing visits to be scheduled inside it. The extent of violation of the 'inconvenient time window' is subsequently minimized as a part of a novel objective function - The patient's inconvenience due to improper scheduling. Another aspect of the same objective function focuses on improving the quality of schedules when scheduling multiple visits to a single patient by clubbing the scattered visits into the minimum possible number of sessions.