CHAPTER 1

INTRODUCTION

1.1 Overview

The World Health Organization (WHO) envisions a world where every mother-to-be (MTB) receives quality care during pregnancy, childbirth, and the postpartum period with no mortality due to avertable causes (Maternal health WHO, 2021). The United Nations (UN) recognizes maternal healthcare as a prime objective in its third sustainable development goal (SDG) of good health and wellbeing. In the SDG, the target for global maternal mortality ratio (MMR) is set to fewer than 70 maternal deaths per 100,000 live births by 2030. The accomplishment of this target would require continued investment in maternal health research and implementation.

Investing in the health of women and children is a smart investment (Malick, 2022). Investing particularly in maternal healthcare not only improves mothers' health but also aids in bringing more women into the workforce and thus fosters the socio-economic wellbeing of communities and nations. This effect was witnessed by the Minister of Health of the Government in Nepal, who stated in June 2008 that investment in maternal healthcare had shown visible improvements in maternal, infant and child health, and the same resulted in the better socio-economic condition in the country. Thus, the maternal mortality rate must be brought down for the betterment of the society and nation (“Investing in Maternal, Newborn and Child Health,” 2009).

As a result of the continuous investment in healthcare, medicinal headways, and rigorous efforts put in by the government and non-government organizations, such as the WHO and United Nations International Children's Emergency Fund (UNICEF), a significant improvement has been witnessed in the status of maternal healthcare across the globe. The global MMR sanked by 44% between 1990 and 2015 (WHO, UNICEF, UNFPA, and Group, 2015). Despite the remarkable decrease in the MMR, the essential interventions for maternal care by the global agencies do not reach the underdeveloped countries. The MMR in low-income countries in 2017 was 462 per 100,000 live births versus 11 per 100,000 live births in high-income countries. The high number of maternal deaths in some areas of the world reflects inequalities in terms of access to the quality health services, and thus it can be attributed to the gap between low and high-income groups of countries. To improve the global status of maternal care, an equitable and accessible healthcare system among the nations and within the nation is much needed.

To improve maternal health, with the support of global agencies, the Indian government has launched several schemes and programs such as Janani Suraksha Yojana–2005, National Rural Health Mission–2005, and Pradhan Mantri Surakshit Matritva Abhiyan–2016. Besides, each community is provided with an Accredited Social Health Activist (ASHA) to look after pregnant women and encourage them to give birth in hospitals and also plan their family size. With all these efforts, India's average MMR per 100,000 live births has diminished from 437 in 1990 to 167 in 2015 (Millennium Development Goals - Final Country Report of India, 2017).

In spite of the significant decline in MMR across the globe and in India, the current figures paint a stark picture. 830 women still die every day in the world due to preventable causes during pregnancy and childbirth. Out of these, 94% of the deaths occur in developing countries (Maternal Health WHO, 2021). In India alone, 120 women die per day on an average due to the causes associated with pregnancy (UNICEF India, 2019). This average is more than 200 in several states of the country (“National Health Profile,” 2018). The current MMR in India is 122 per 100,000 live births. This improvement in MMR is being witnessed due to the continuous efforts of the governmental and non-governmental agencies and the ascent in the number of institutional deliveries. India still needs an aggressive plan for a better maternal healthcare system. According to a recent report, only 54.7% of estimated deliveries occurred in a health facility (NITI Aayog, 2020). The situation is worse in rural areas because the MTBs in this areas do not take medical advice during pregnancy, and reach health facilities only at maturity. Due to this, maternal mortality is observed to be higher in rural areas and that to be more among impoverished communities. Rural Health Statistics (2014-15) indicates that there is a deficit in the required number of Sub-Centers, Primary Health Centers, and Community Health Centers to take care of growth in the size of the population, regardless of the investments in the National Rural Health Mission throughout the recent decade (Ministry of Health and Family Welfare, 2015). It is why an increase in the institutional childbirth did not leave the expected impact on the maternal mortality due to the inability in providing much-needed emergency obstetric and neonatal cares. In order to reduce maternal mortality and child health, it is imperative that the health centers be equipped with better facilities to address and arrest complications during pregnancy, deliveries, and neonatal care. Fortification of the health facilities at all levels is the need of the hour to ensure the comprehensive provision of antenatal, delivery and postnatal care. Emergency readiness, including the availability of a transport facility and a streamlined referral framework, is also a must.

In India, the forecasted births were expected to be 20.1 million in the first nine months after the announcement of the COVID-19 pandemic (United Nations, 2020). Pregnant women were not facing serious danger due to COVID-19 but needed access to antenatal, delivery and postnatal services (UNICEF, 2021). However, the COVID-19 pandemic revealed profound fundamental issues with the Indian healthcare system. During the pandemic, pregnant women and their babies faced crises and strained healthcare facilities, including overcrowded health centers, supply and equipment shortages, and a lack of skilled birth attendants such as midwives. Dealing with the ascent in the number of births with an ongoing pandemic was a big challenge for the Indian maternal healthcare system. It exposed the level of preparedness of the Indian maternal healthcare system in such an unforeseen situation where even routine check-up became a challenge for MTBs.

The accomplishment of the target on global MMR will require continued investment in maternal healthcare in the country to address the various challenges. Many challenges lie in the Indian healthcare system. Some of these, related to maternal healthcare, are addressed in the following section.

1.2 Challenges in Maternal Healthcare in India

1.2.1 Availability and accessibility

Around 69% of the population in India lives in rural areas, and most of them are below the poverty line. Different surveys reveal that many MTBs from rural areas cannot meet the courses recommended by WHO, such as, four check-ups and fetus assessments during the antenatal period, dietary requirements, and necessary vaccinations during the antenatal and neonatal periods. The report of the Comptroller and Auditor General of India cites the lack of accessibility and availability of the maternal healthcare facilities as the most critical factors leading to the inferior status of maternal healthcare in the country (Ministry of Health and Family Welfare, 2017). Figure 1.1 depicts the current state of affairs existing in rural area of the country. In many places, pregnant women have to travel a long distance to reach the healthcare units to avail primary or higher-level services. Due to this, institutional deliveries are not remarkable in many parts of the country. Therefore, improving the 'availability' and 'accessibility' of the maternal healthcare facilities will advance and enhance the healthcare of MTBs in India.

Figure 1.1: Cases related to accessibility issues of healthcare facilities in rural areas

1.2.2 Service quality

Service quality in maternal healthcare plays a major role in achieving health coverage and equity. It also helps in reducing maternal and neonatal mortality. Poor quality services are responsible for 6 out of 10 neonatal problems and half of the maternal fatalities in developing nations (WHO, 2022). Deterioration in service quality is due to overburdening of the health facilities and overstretching of the healthcare workers, and also due to resource unavailability. The quality concerns would desire that the capacity of the healthcare facility is duly acknowledged during the planning phase itself. It would ensure service quality during operation. During the healthcare facility planning, it is essential to ensure that enough number of maternal healthcare facilities are available to meet the current and future demands. The study undertaken in this thesis addresses this concern.

1.2.3 Population growth

Demographic projections (Economic survey, 2019) show that India's population growth will continue to slow over the next two decades, being less than 1% during 2021-31 and under 0.5% during 2031-41, with a few Indian states accounting for more than 40% of the total growth. However, the population density will rise from 368 people per square kilometer in 2011 to 463 in 2036. Figure 1.2 shows that the female population in 2036 will be largest, in the age group of 25 and 34. This is also the age group in which the most births have been reported. Thus, there is an urgent call for planning a healthcare network to meet these upcoming challenges, given that access to a healthcare facility is still a significant challenge in India. The rising population and density over the following twenty years (even with the slow population growth rate) will sharply diminish the per capita availability of hospital beds in India across all the major states. States with high population growth will suffer the most in terms of hospital bed availability. Hence, there is a straightforward case for expanding healthcare facilities, particularly in India.

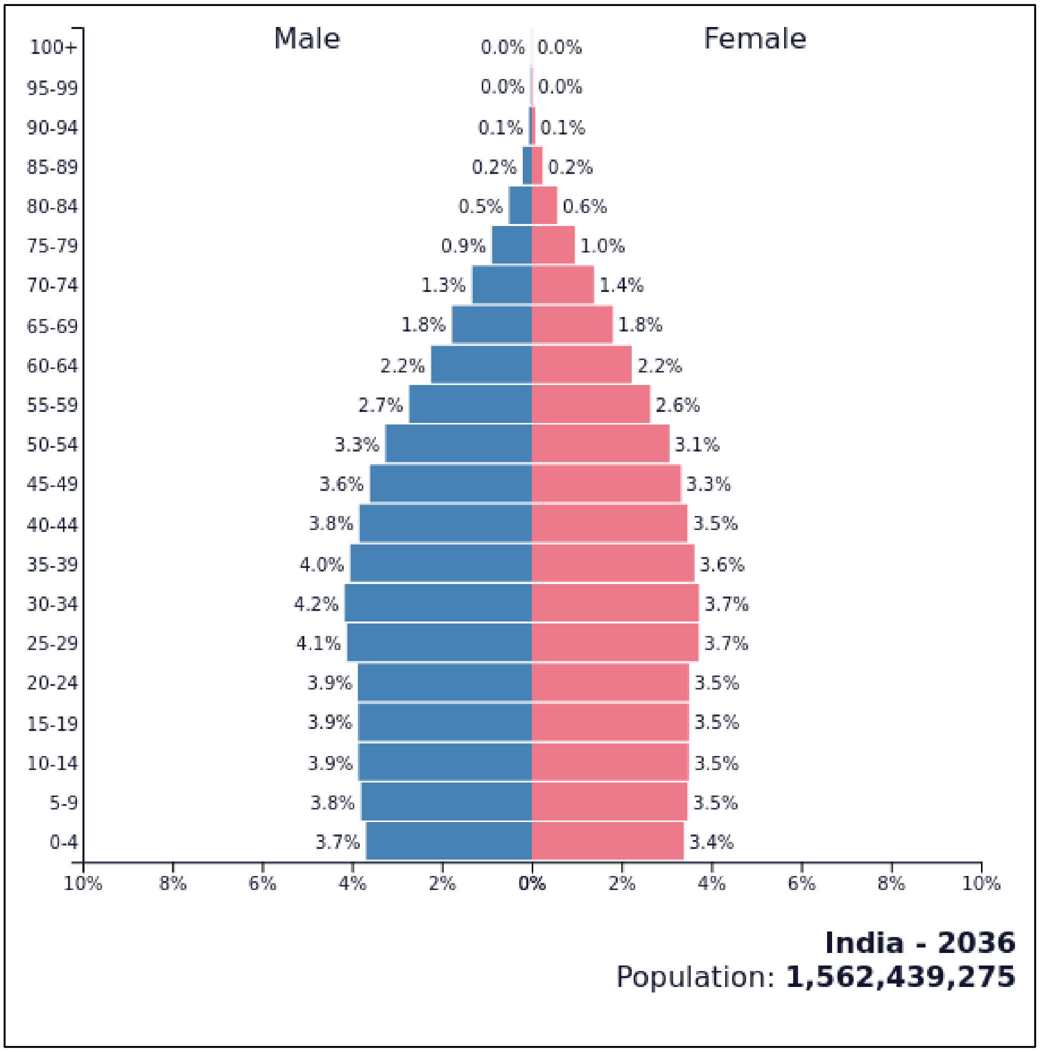

Figure 1.2: Demographic projection of India in 2036

(Source: Ministry of Health & Family Welfare, 2020)

1.3 Literature Review

An extensive literature review was carried out related to maternal healthcare problem and challenges. This review has helped in identifying scientific contributions made by the researchers to the healthcare facility location and allocation problems. An understanding of the previous research efforts in the domain of the Healthcare Facility Location Problem (HFLP) has helped in identifying the research gaps, particularly related to the research problem undertaken in the present thesis work. The related research work has been discussed in brief in the following sub-sections.

1.3.1 Facility location problem

The Facility Location Problem (FLP) is a classic optimization problem that involves determining the best location for a factory or a warehouse based on geographic demands, facility costs, and transportation distances. The decision related to identifying proper location of a facility is important because a poorly located facilities can significantly affect the overall system. FLP also addresses the issue of allocation of demand to the facilities. The first study on FLP was done by Weber (1909), who considered a warehouse location problem with the objective of minimizing the total distance between a warehouse and the various customers. Following that, the work on facility location problem and its wide range of applications has been seen in various research areas such as planning and modelling of production-distribution systems (Aardal, 1998; Gao and Robinson, 1992; Hinojosa et al., 2000; Pirkul and Jayaraman, 1998; Ro and Tcha, 1984; Scott, 1971; Tcha and Lee, 1984; Tragantalerngsak et al., 1997; Van Roy, 1989; Widener and Horner, 2011), solid waste management systems (Barros et al., 1998), education systems (Teixeira and Antunes, 2008), postal delivery services (Sheu and Lin, 2012) and healthcare system (Galvão et al., 2002; Galvão et al., 2006; Ghaderi and Jabalameli, 2013; Jang and Lee, 2019; Khodaparasti et al., 2017; Ndiaye and Alfares, 2008; Rahman and Smith, 1999; Tien and El-Tell, 1984). Framework of FLPs can also be applied to other contexts, such as stochastic, hierarchical, hub, dynamic and online location problems, competitive location problems, and so on (Laporte and Dejax, 1989). The integration of location decisions with other important logistical considerations became an increasingly important topic in the literature of FLPs. Location-inventory problems (Daskin, 2011; Farahani et al., 2015), location-routing problems (Javid and Azad, 2010; Prodhon and Prins, 2014), location-routing-inventory problems (Javid and Seddighi, 2012), location-pricing problems (Javid and Hoseinpour, 2015a), and location-inventory-pricing problems (Javid and Hoseinpour, 2015b) are the examples of this integration. The FLPs can be broadly categorized into continuous and discrete based on the space in which they are modelled (Re Velle et al., 2008). In continuous FLPs, facilities can be located anywhere in the considered feasible space while in discrete FLPs, facilities will be located only at candidate locations which may include demand points also. The literature discussed further is focused on discrete FLPs and related to healthcare only, and maternal healthcare facility location problem in particular.

1.3.2 General healthcare facility location problem

The problem of locating a healthcare facility is more critical than similar problems in other areas because incorrect location decisions for healthcare facilities may have a serious impact on the public and society. This will not only lead to high service cost and low-quality service but also to increased morbidity and mortality. Furthermore, healthcare and the associated Healthcare Facility Location Problems (HFLPs) have become noticeably more critical and important to society due to the prevalent worldwide trend of decreasing birth rates, higher life span and associated growth in the ageing population, and rising environmental problems. As a result of this, HFLPs and modelling continue to pique the interest of the operations research community.

Gould and Leinbach (1966) were the first to mathematically model FLP along with the allocation problem to determine the location of hospitals and their capacities in the western part of Guatemala. Their work was enriched and extended by several researchers in different application contexts. Javid et al. (2017) offered a comprehensive survey on the problem and models of HFLP, as well as their application to various healthcare sectors. Their survey shows the directions in which healthcare facility location models have been extended over time with the incorporation of various elements of healthcare problem. The problem of healthcare facility location has not only gained much importance in locating the health facility and allocating the patients to them, but it has also served as the foundation for research into other modern healthcare facility location issues, such as long-term nursing care centers (Cardoso et al., 2015), home health care centers (Gutiérrez and Vidal, 2013), and mobile health care units (Doerner et al., 2007). HFLPs addressed a wide range of issues and systems, such as healthcare operations management, healthcare services supply chains (Vries and Huijsman, 2011; Dobrzykowski et al., 2014), services supply chains (Wang et al., 2015), pharmaceutical supply chains (Lemmens et al., 2016; Narayana et al., 2012; Shah, 2004), healthcare waste management (Thakur and Ramesh, 2015), disaster operations management (Altay and Green, 2006; Hoyos et al., 2015), emergency logistics, relief distribution, humanitarian logistics (Caunhye et al., 2012; Gutjahr and Nolz, 2016; Özdamar and Ertem, 2015), homeland security (McLay, 2015; Wright et al., 2006), emergency response (Simpson and Hancock, 2009), emergency response stations (Başar et al., 2012), emergency services vehicles (Snyder et al., 2016). This illustrates that HFLP framework has found their application in a wide range of fields.

In light of the diverse spectrum of healthcare and medical services available, Javid et al. (2017) divided HFLPs into two groups: non-emergency and emergency facility location problems. Non-emergency FLPs are problem of locating primary healthcare centers (PHCs) (such as hospitals and clinics), blood banks, pathology centers, organ transplant centers and medical stores; whereas locating trauma centers, ambulance stations, temporary medical centers and points of dispensing are the example of emergency FLPs. Javid et al. (2017) conducted a review of over 200 research articles and found that nearly half of the papers concerned non-emergency HFLPs. It is interesting to note that, more than 50% of these papers address the problem of the location of PHCs. It is the determination of the locations of PHCs that has been drawn great amount of attention of operation research community for many years.

In general, healthcare facilities have multiple levels and may generally offer three types of care: primary, secondary, and tertiary care (Frontenders, 2018). The lowest level facility provides primary care services such as routine check-ups, colds, flu, and other bacterial or viral infections to direct incoming patients. The middle-level facility offers secondary care services which require the inclusion of specialists such as cardiologists, dermatologists, urologists, and other experts. It also manages referrals from the lower level and offers primary care. The highest level facility in the hierarchy provides all the primary and secondary level services besides tertiary care services that covers major procedures, transplants, and the treatment of patients referred from primary and secondary care units. Such a type of planning network of healthcare facilities can be viewed as a hierarchical (i.e., a system of different types of interacting facilities) and inclusive (i.e. higher-level facility also provides a lower level of services) healthcare facility location problem (HFLP). The review papers by Şahin and Süral (2007) and Farahani et al. (2014) provide a comprehensive survey of the literature on hierarchical facility location problems and discussed many mathematical models that represents variety of HFLPs. The framework of HFLP has been applied to a variety of fields, including solid waste management (Barros et al., 1998), education systems (Teixeira and

Antunes, 2008), fire protection (Schilling et al., 1979), and telecommunication networks (Chan et al., 2008).

Narula and Ogbu (1979) developed a hierarchical location-allocation mathematical model by including referrals under the assumption of sufficient available capacity for fulfilling the demand. Their work has been enriched by various researchers by considering different problem objectives such as minimizing the total weighted travel distance or maximizing the coverage. Further work considered many other problem attributes, such as, hierarchical nature, referral, budget and capacity limitations and many others. A review of the related research papers is presented below considering the various features of or associated with HFLP, such as, modelling approach, factors and parameters considered, etc.

1.3.2.1 Modeling approach

The mathematical modelling approach utilized by several researchers in planning the network of healthcare facilities draw the essence of set covering, maximal covering, *p*-center, *p*-median and fixed-charge facility location framework. The objective of the set covering model is to determine the minimum number of facilities that are needed to cover all the demand nodes. In many of the cases, set covering model may call for locating number of facilities more than the number of facilities what the budget may permit. Under such circumstances, the alternative strategy would be to maximize the number of demand nodes that can be covered with a given number of facilities while achieving specified service level constraints. The concerned mathematical model is known as the maximal covering model. The basic set covering model was further extended to minimize the maximum distance between a demand node and the nearest facility node. In some cases, instead of the maximum distance, the maximum of demand weighted distance was minimized. Such a problem is known as *p*-center problem. This

Table 1.1: Summary of the research papers related to locating healthcare facilities based on the modeling approach

Model framework	Particulars of research work
Set Covering	Chu (2000), Kim et al. (2012)
Maximum Covering	Griffin et al. (2008), Güneş et al. (2014), Kim and Kim (2013), Marianov and Taborga (2001), Marianov et al. (2004), Mestre et al. (2015), Ratick et al. (2009), Shariff et al. (2012)
p-median	Galvão et al. (2002), Mitropoulos et al. (2006), Beheshtifar and Alimoahmmadi (2015), Mestre et al. (2012), Smith et al. (2009), Mitropoulos et al. (2013)
Fixed-Charge	Cocking et al. (2012), Graber et al. (2015), Rahmaniani et al. (2014), Shishebori and Babadi (2015), Stummer et al. (2004), Ndiaye and Alfares (2008), Ghaderi and Jabalameli (2013a), Mestre et al. (2015)

type of modeling approach has wide application in ambulance location problems. Because of the objective of public healthcare facilities is to cover all the demand nodes, the problem is also formulated as a *p*-median model. Here, the objective is to minimize the overall cost by minimizing the average distance between demand and facility nodes (or total demand weighted distance) using '*p*' number of facilities (Kariv and Hakimi, 1979). These facility location models do not consider the establishment cost of the facility, or it is assumed that the cost of constructing a facility was the same at each candidate facility site. This will not be the case always. The underdeveloped and developing countries do not have abundance of funds. For them, it is always a challenge to have full health coverage with limited funds. In planning of healthcare facilities network, such countries are bound to give due consideration to fixed cost in establishing such facilities. While the fixed cost of establishing the healthcare facility are generally borne by the government, and the travelling cost is naturally borne by the patients. In order to strike a balance between both the type of costs it is important to determine the optimal number and location of the healthcare facilities in such a way that it should cover the population and should be available within the reach of individuals. Fixed-charge facility location model takes care of this consideration. The objective of the fixed-charge facility location model is to minimize the total cost, which includes total demand-weighted distance and cost of establishing the facility.

The researchers have used different modelling framework depending upon the problem type considered. The summary of those works is provided in Table 1.1.

1.3.2.2 Type of healthcare facilities

The primary healthcare facilities are generally hierarchical in nature. Facilities are called hierarchical in terms of the type of services being offered by them. It is observed that a vast majority of researchers have worked on non-hierarchical healthcare facilities, such as basic health units, which provide only single type of service. Only a few researchers have attempted to formulate the healthcare problem with hierarchical facilities. The maternal healthcare facilities considered in this study is hierarchical and successively inclusive in nature. Table 1.2 summarizes the available literature on planning of hierarchical and non-hierarchical healthcare facilities.

Table 1.2: Summary of research papers related to the type of healthcare facilities

Type of healthcare facilities	Particulars of research work
Hierarchical	Galvão et al. (2002), Mestre et al. (2012 and 2015), Ratick et al. (2009), Smith et al. (2009)
Non-hierarchical	Beheshtifar and Alimoahmmadi (2015), Chu (2000), Cocking et al. (2012), Ghaderi and Jabalameli (2013a), Graber et al. (2015), Griffin et al. (2008), Güneş et al. (2014), Kim et al. (2012), Marianov and Taborga (2001), Marianov et al. (2004), Mitropoulos et al. (2006), Ndiaye and Alfares (2008), Ares et al. (2016), Oliveira and Bevan (2006), Rahmaniani et al. (2014), Shariff et al. (2012), Shishebori and Babadi (2015), Stummer et al. (2004)

1.3.2.3 Capacity

Many of the authors have formulated the HFLPs by considering the healthcare facilities as uncapacitated. The models proposed by those researchers have limited acceptance in practice due to the implicit assumption of the infinite capacity of healthcare facilities. Allocation of significantly large number of patients to a health center is going to affect the quality of the service provided by the center. To arrest such a problem, many authors have come up with hierarchical location models considering finite capacity of facilities. This study also considered the finite capacity of the maternal healthcare facilities to maintain the service quality. The classification of the literature based on this factor is shown in Table 1.3.

Table 1.3: Summary of the research work related to capacity consideration

Healthcare facility	Particulars of research work
Uncapacitated	Beheshtifar and Alimoahmmadi (2015), Chu (2000), Cocking et al.(2012), Galvão et al. (2002), Graber et al. (2015), Kim and Kim (2013), Marianov and Taborga (2001), Marianov et al. (2004), Mestre et al. (2015), Mitropoulos et al. (2013), Ndiaye and Alfares (2008), Ares et al. (2016), Rahman and Smith (1999), Ratick et al. (2009), Smith et al. (2009)
Capacitated	Güneş et al. (2014), Mestre et al. (2012), Mitropoulos et al. (2006), Oliveira and Bevan (2006), Rahmaniani et al. (2014), Shariff et al. (2012), Shishebori and Babadi (2015)

1.3.2.4 Coverage distance

Coverage distance refers to the maximum allowable distance that is reasonable for a person to travel to obtain the healthcare service. Few authors have considered the coverage distance for general healthcare (shown in Table 1.4). Jang and Lee (2019) have considered the coverage distance for planning neonatal care facilities in Korea. In the case of maternal care, distance becomes a significant challenge because a pregnant woman cannot travel a much longer distance during pregnancy for regular check-ups or at the time of labour pain. Coverage distance becomes an important consideration for referral cases also. Many of the times, lower-level facility in rural areas did not find any nearby higher-level referral facility during emergencies. Seemingly, none of the studies has addressed the coverage distance issue for referral cases for maternal care. The present work takes care of this concern.

Table 1.4: Summary of the research work related to coverage distance consideration

Coverage distance	Particulars of research work
non-referral	Griffin et al. (2008), Güneş et al. (2014), Mitropoulos et al. (2006), Rahman and Smith (1999), Shariff et al. (2012), Benneyan et al. (2012), Jang and Lee (2019)
referral	Jang and Lee (2019)

1.3.2.5 Referral

In hierarchical HFLPs, since one facility does not provide all types of services, a referral to higher level facility is required. Many of the authors shown in Table 1.5 have considered referral from a lower level to a single higher level of the facility in the hierarchical system. Nowadays, it is common to find referral from lower levels to a good majority of higher level facilities, particularly in India. None of the authors have considered this aspect in the case of maternal health care. In the case of maternal care, an emergency can arise for any type of higher-level service from any type of facility. The model presented in this work provides the referral from lower-level facility to any relevant higher-level facility within the coverage distance.

Table 1.5: Summary of the research work related to referral consideration

Referral consideration	Particulars of research work
single service type	Narula and Ogbu (1979), Tien et al. (1984), Rastaghi et al. (2018), Zarrinpoor et al. (2018), Jang and Lee (2019)
all service type	None

1.3.2.6 Types of cost

Another aspect seen in the HFLPs literature is related to the consideration of the various types of cost. These costs are the cost of travel incurred by the patients in visiting the healthcare facility, the cost of referral from one facility to another and the cost of establishment. In literature, authors have used different costs in an objective function based on their modelling approach. Cost related to unfulfilled demand is observed in the work of Mestre et al. (2015). The demand may remain unfulfilled due to the limited capacity of facility available within the coverage distance. They considered the penalty cost for the lost demand to seek the tradeoff between unsatisfied demand and excessive capacity. Instead of losing the patient, another approach could be allowing overburdening of the facilities with high penalty cost. The high penalty cost could be associated with extra hours working of healthcare personnel's. It may also be attributed to fall in the quality of service. The work undertaken in the present research allowed the allocation of MTBs to the facilities beyond the capacity at a penalty cost. The consideration of penalty cost will try to find out an optimal tradeoff between the number of facilities to be established and excess of allocations. This consideration has not been witnessed in any study till now. The summary of various types of cost used in the literature is shown in Table 1.6.

Table 1.6: Summary of the papers related to various types of costs

Types of cost	Particulars of research work
Travel cost	Beheshtifar and Alimoahmmadi (2015), Cocking et al. (2012), Galvão et al. (2002), Graber-Naidich et al. (2015), Güneş et al. (2014), Mestre et al. (2012 and 2015), Mitropoulos et al. (2006), Stummer et al. (2004), Mitropoulos et al. (2013)

Establishment Cost	Beheshtifar and Alimoahmmadi (2015), Graber et al. (2015), Rahmaniani et al. (2014), Shishebori and Babadi (2015), Stummer et al. (2004)
Penalty for overloading	None
Penalty for lost demand	Mestre et al. (2015), Rastaghi et al. (2018)

1.3.2.7 Time-frame

In the late 70's, Manne (1961) and Ballou (1968) added another dimension to the HFLP literature by proposing multi-period facility location models. Earlier, HFLP models, assumed demand and costs to be deterministic and not to change with time. The demand is time-varying and experiences growth in general. Besides, transportation and operation costs may also vary with time. The multi-period location models available in the literature consider these variations and determine the location of facilities in optimal time periods while minimizing the total costs for serving demand and for operating and relocating the facilities over the planning horizon. After that, much work has been done on the multi-period facility location, and many models have been developed. These models address the dynamic single facility location problem (Farahani et al., 2009), dynamic multi-facility location problems (Dias et al., 2007; Scott, 1971), dynamic *p*-median problem (Drezner, 1995), dynamic set covering problem (Chrissis et al., 1982), location-routing problem (Laporte and Dejax, 1989), and dynamic multi-echelon facility location problem (Sambola et al., 2009; Hinojosa et al., 2000). One can refer to the work of Soto (2009) and Farahani et al. (2009) for a comprehensive review of the literature on this dimension.

Current et al. (1997) have divided dynamic location models into explicit and implicit models. In explicit models, the opening and closing of facilities can occur any time during the planning horizon. In implicit models, all the facilities are to be opened at the beginning of the planning horizon, and the same remains open throughout the planning horizon. In healthcare network planning, implicit models are generally considered because the decision of closing an opened healthcare facility seems unrealistic. As the population increases during the planning horizon, the existing facilities are required to be upgraded depending upon the demand of various service types. In multi-period healthcare planning, some researchers consider the possibility of capacity expansion, opening of new facilities or upgrading of existing healthcare facilities. The details of the reviewed literature in the single and multi-period settings are given in Table 1.7.

Particularly for healthcare, Ndiaye and Alfares (2008) developed a binary integer programming model to determine the optimal number and location of primary healthcare units for a seasonally varying nomadic population in the Middle East. Benneyan et al. (2012) developed single and multi-period location-allocation models for the Veterans Health Administration for their specialty care to reduce the total cost and total travel distance while increasing the access within the healthcare network. Their multi-period models permit capacity expansion and the opening of new facilities in any year. To meet the increasing demand of various types of healthcare services, it is necessary to increase the capacity and provide additional types of services to the existing ones. In our work, the up-gradation of the facility is considered. Upgradation includes addition of new services and enhancement of the capacity of the existing services. Cardoso et al. (2012) proposed a simulation model based on the Markov cycle to capture the future annual demand for long-term care networks. In another work, Cardoso et al. (2015) proposed a multi-objective and multi-period model for the long-term care sector, considering deterministic demand in the Great Lisbon region in Portugal. Location of new facilities in each time period, distribution of capacity, redistribution of existing capacity and allocation of patients in each time period is determined by three equity objectives: equity of access, geographical equity, and socio-economic equity. Ghaderi and Jabalameli (2013) considered deterministic demand in their budget-constrained, multi-period, and uncapacitated facility location-allocation model for planning healthcare facilities in Iran. In a recent work on long-term care, Intrevado et al. (2019) proposed a multi-period MILP model to open new facilities and expand existing facilities for varying deterministic demand.

Table 1.7: Summary of the research work based on time-period consideration

Time period	Particulars of research work
Single period (static)	Chu (2000), Beheshtifar and Alimoahmmadi (2015), Graber et al. (2015), Kim and Kim (2013), Marianov and Taborga (2001), Ares et al. (2016), Rahmaniani et al. (2014), Ratick et al. (2009), Shishebori and Babadi (2015), Smith et al. (2009), Galvão et al. (2002), Mitropoulos et al. (2006), Oliveira and Bevan (2006), Griffin et al. (2008), Smith et al. (2009), Mestre et al. (2015), Shariff et al. (2012), Marianov et al. (2004), Mitropoulos et al. (2013)
Multi-period (dynamic)	Ghaderi and Jabalameli (2013b), Mestre et al. (2015), Ndiaye and Alfares (2008), Stummer et al. (2004)

1.3.2.8 Case Study

Most of the authors have presented case studies to demonstrate the applicability of their models. During the literature survey, it was found that most of the reported case studies are from underdeveloped and developing countries from the Asian continent. However, none of the studies has been carried out in the Indian context.

1.3.2.9 Problem solving approach

The HFLPs are well known NP-hard problems (Daskin, 2009; Megiddo and Supowit, 1984). These are the problems with no known polynomial-time exact solution algorithm. The time required to exactly solve these problems may increase rapidly (exponentially shown in Chapter

3) as the size of the problem grows. Because of this, a variety of exact algorithms, metaheuristics and heuristics can be found in the literature to obtain optimal or near-optimal solutions to HFLPs. The solution approach is called an exact approach if it provides an optimal or near-optimal solution with a known deterministic error bound or optimality gap. In the use of metaheuristic or heuristic, one cannot predict the exact quality of the resulting solution, since it does not guarantee an error bound, these methods are called inexact solution approaches.

Table 1.8: Summary of research work based on the approaches applied to solve HFLPs

Problem solving approach	Particulars of research work
Lagrangean	Galvão et al. (2002), Galvão et al. (2006), Kim and Kim (2013)
Benders	Soto (2009)
Heuristic	Ghaderi and Jabalameli (2013a), Marianov and Taborga (2001)
Metaheuristics	Tabu search - Stummer et al. (2004) Genetic algorithm - Shariff et al. (2012), Beheshtifar and Alimoahmmadi (2015) Simulated Annealing - Ghaderi and Jabalameli (2013a)

In the literature on HFLP, it is found that researchers have used both exact and inexact approaches. The summary of these approaches is presented in Table 1.8. Many of the authors have used branch and bound method and Lagrangean relaxation as exact approaches. Some have also used the Benders decomposition approach as an exact method. It is worth mentioning that to solve the HFLP using the exact approach, the researchers have used state of the art solver such as CPLEX, LINGO, and GAMS, etc. Very few have used Gurobi to follow branch and bound methods for solving HFLP. Since, exact methods fail to provide even a feasible solution within a reasonable time limit, the researchers have used various metaheuristic approaches such as simulated annealing, genetic algorithm, ant colony and Tabu search. Some researchers have used problem-specific heuristics to obtain a feasible solution in real-time.

1.4.4 Maternal healthcare facility location

The research studies mentioned so far are not targeted to address the concerns of MTBs. Limited work is available on the planning of the healthcare facilities, particularly for MTBs. For perinatal care, Galvão et al. (2002) proposed a hierarchical facility location model. They created an uncapacitated three-level successively inclusive hierarchical location model for Rio de Janeiro, Brazil, to identify the optimal sites for perinatal care during childbirth and the postpartum period. They chose to locate a predetermined number of facilities while keeping the users' travel costs to a minimum. They classified healthcare facilities into three categories depending on the services these offer. Referrals for a higher level of service were also considered. They later revised their uncapacitated model to account for the limited capacity of the highest level health facility's (Galvão et al., 2006). In Indian context, their problem framework cannot be applied as such for the reason as follows. Their model considered referrals from a lower-level facility to a single higher-level of facility. In Indian context, referrals are made from Sub Centers (SCs) to Primary Helathcare Center (PHCs) and Community Healthcare Centers (CHCs), and similarly from PHCs to CHCs for certain type of services. Their model is all about locating a fixed number of facilities (*p*-median formulation). In the Indian context, the government's desire of covering all MTBs under the net of government established healthcare centers cannot allow the planner to determine the exact number of these facility types particularly when coverage distance limitation is also to be considered in planning the network.

Baray and Cliquet (2013) initially addressed the problem of selecting locations for the new facilities. They next try to choose areas from these selected locations for the establishment of facilities successively for higher levels, these facilities offer unique services not available at other levels. In India, the maternal healthcare facilities do not have this sense of exclusivity, and a higher level, center has to provide services rendered even by the lower-level centers. Jang and Lee (2019) and Jang (2019) have also adopted Baray and Cliquet (2013) unique viewpoint on the types of healthcare facilities required for neonatal healthcare planning in South Korea. Their *p*-median approach, along with the finite capacity of the facilities, makes it very difficult to guarantee complete coverage that otherwise might require an increase in '*p*'.

1.4.5 Bibliometric mapping

A bibliometric mapping of the publications related to FLPs has been built to analyze the literature quantitatively. For this purpose, the Scopus database is selected for the literature review of the technical articles. The Scopus database is the largest abstract and reference source of peer-reviewed literature. In the Scopus database, various combination of words is searched by using 'AND', and their results are shown in Table 1.9. The search included technical articles, articles in the press, books, book chapters, conference reviews, conference articles, editorials, notes, short surveys, review articles, etc. co-occurrence analysis of the author keywords was performed to find the significant terms utilised in these documents. The keywords related to each article have been extracted from a comma-separated value (.csv) file from the Scopus database. The co-occurrence network map was created with the help of VOSviewer®. The entire number of keywords is separated into clusters, which are shown on the map in different colours. The size of the circle indicates the frequency of the keyword occurrence, and the proximity of the circles indicates the co-occurrence of the keywords, i.e., the closer the two circles are, the higher the frequency of their co-occurrence (van Eck and Waltman, 2014). One will find these keywords useful in locating HFLP related literature.

Table 1.9: Number of research articles found in the Scopus database

Keyword searched (Title-abs-key)	Scopus results
Facility location	44,308
Healthcare facility location	1539
Hierarchical facility location	591
Hierarchical healthcare facility location	37

The Scopus results show that facility location is a broad term that results in a large number of documents. The term 'Healthcare facility location' is searched to keep our search limited to the scope of the study, and it returns 1539 documents. Because the search is further narrowed by utilizing the key phrase 'hierarchical,' a small number of documents are found. The bibliometric mapping is performed using documents found through a search for the term 'Healthcare facility location.' A total of 10885 keywords were found in 1539 documents. When the minimum occurrence bar was set to 20, the number of keywords was reduced to 248 and grouped into four clusters, as illustrated in Figure 1.3. This Figure 1.3 shows that the terms healthcare facility and healthcare services have limited occurrence in the literature, while the term maternal health services rarely appear in comparison to other keywords. To further investigate the frequency of occurrence of these terms in literature, the minimum occurrence bar was adjusted to 5, bringing the total number of keywords to 1319 and grouping them into seven clusters. In Figure 1.4, many relevant key terms are visible in this setting, including maternal health service, pregnancy, midwife, prenatal care, childbirth, primary health care, and accessibility, all of which have a connection to healthcare. This bibliometric mapping reveals that research on maternal healthcare facility location is scarce. Through the present research work, an effort has been made to bridge this gap in the literature related to maternal healthcare facility location.

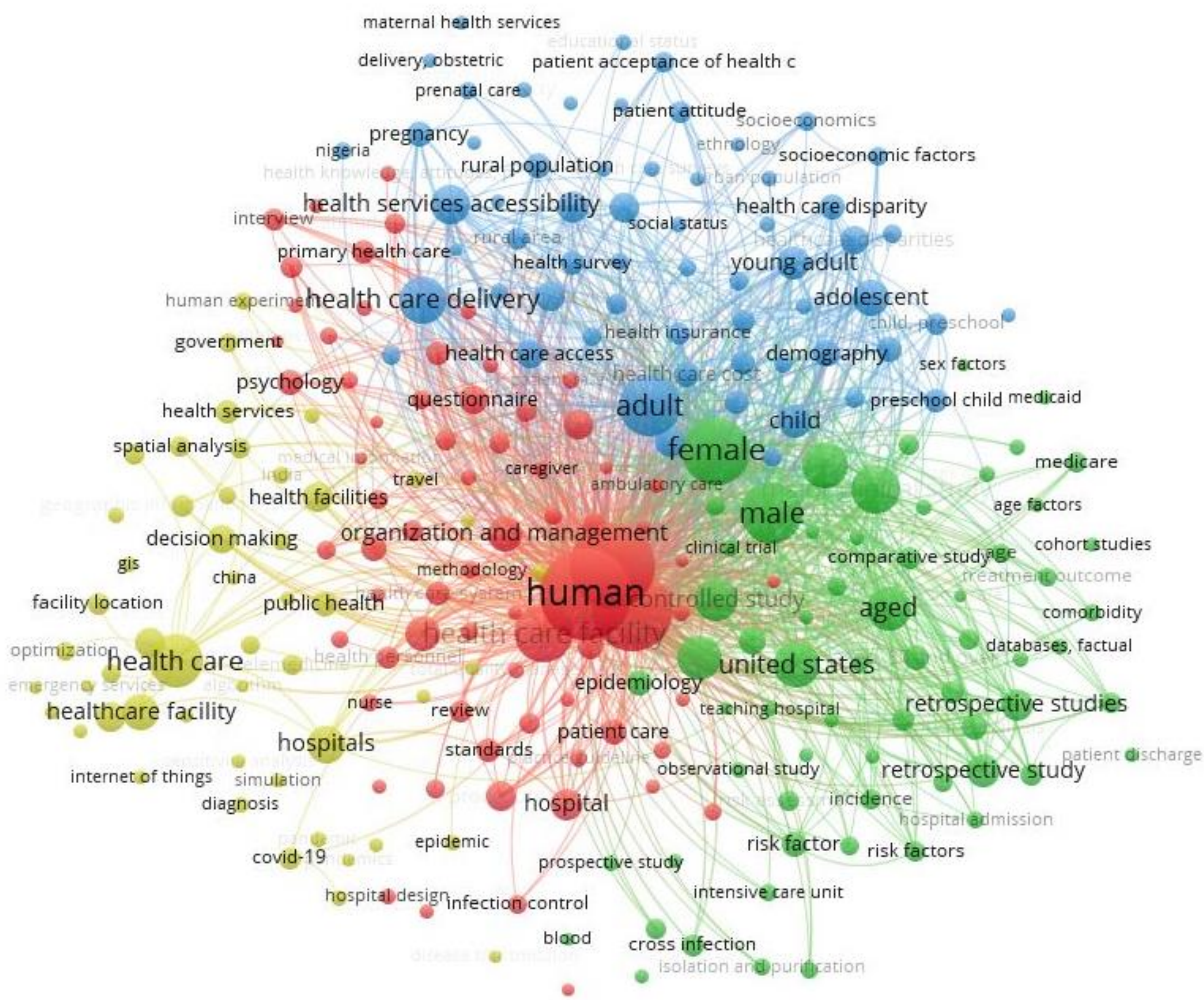

Figure 1.3: Network visualization for minimum co-occurrence as 20

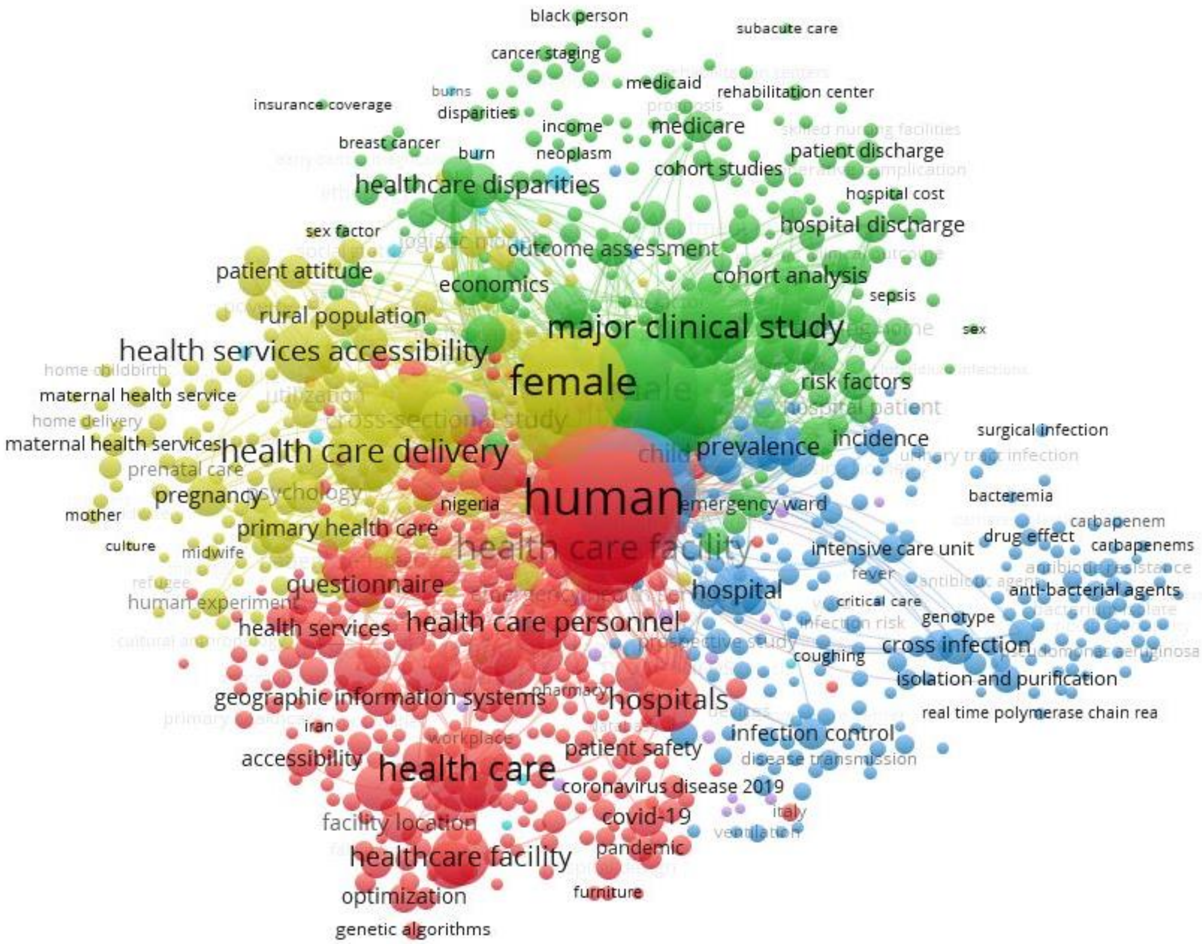

Figure 1.4: Network visualization for minimum co-occurrence as 5

1.4 Research Gaps

After reviewing the literature on HFLP for general healthcare and specifically for maternal health care, many gaps have been identified providing research directions for the present work. The summary of the literature review and gaps are shown in Table 1.10 and presented below.

- Many of the authors treated HFLPs as a *p*-median formulation. This formulation will not arrest the limit on coverage distance which is an important consideration for planning maternal healthcare facilities.
- There is no work available related to establishing the maternal healthcare facilities where coverage distance issue is addressed both for referral and non-referral cases. Coverage distance issues addressed by Jang and Lee (2019) are limited to only referral cases, and that too for neonatal care.
- Galvão et al. (2002) and Galvão et al. (2006) addressed referrals only from mid-level facilities to highest level facilities. When it comes to maternal care, having a higher level facility as a referral unit for each lower-level facility is important. This consideration has not been addressed so far.
- The majority of published research publications regard maternal healthcare facilities as uncapacitated. Galvão et al. (2006) have so far given due recognition to the capacity of higher-level facilities. In practice, every health facility has a typical capacity beyond which the service quality inevitably suffers.
- It is further observed that the maternal healthcare planning problems considered so far are a single-period problem. Given the growth in the population, attempting to develop a multi-period facility location-allocation model for maternal healthcare will be definitely desirable.

- Available multi-period non-hierarchical network of healthcare facilities are successively exclusive. No work is available for successively inclusive multi-period planning of maternal healthcare facilities.
- Very few authors have attempted to propose heuristic approaches to solve the maternal healthcare facility location problem in a computationally efficient manner. None of the authors have used Benders decomposition to solve maternal healthcare location-allocation problems in multi-period settings.

Table 1.10: Summarized literature review

References	Objective: To minimize total weighted travel	To maximize coverage	To minimize Total cost	Modelling approach	Multi-period	Capacitated	Referral	Fixed cost	Coverage distance for non-referral	Coverage distance for referral	Solution approach	Case study
General healthcare facility location allocations												
Narula and Ogbu (1979)	✓			PM		✓	✓				H	
Chrissis (1982)				SC	✓						AT	
Gunawardane (1982)				SC	✓							
Tien et al. (1984)	✓			PM			✓					Jordan
Drezner (1995)	✓			PM	✓						H	
Current et al. (1997)	✓			PM								
Rahman and Smith (1999)				MC					✓			Bangladesh
Hinojosa (2000)			✓	FC	✓	✓		✓			L	
Melo (2005)			✓	FC	✓	✓						
Mitropoulos et al. (2006)	✓			PM		✓ ε			✓			Western Greece
Dias et al. (2007)			✓	FC	✓						H	
Griffin et al. (2008)		□		MC		✓		✓	✓		H	Georgia
Ndiaye and Alfares (2008)			✓	FC	✓			✓				Middle East
Antunes et al. (2009)	✓			MC	✓	✓						Portugal
Lee (2009)			✓	FC	✓	✓					AA	
Sambola (2009)			✓	FC	✓			✓			L	
Soto (2009)			✓	FC	✓	✓					L & B	

ED Gunes and H Yaman (2010)			✓			✓		✓	✓			Turkey
Shariff et al. (2012)		□		MC		✓			✓		GA	Malaysia
Benneyan et al. (2012)			✓	FC	✓	✓		✓	✓			England
Ghaderi and Jabalameli (2013)			✓	FC	✓			✓			SA	Iran
Delmelle et al. (2014)	✓			FC	✓	✓						North Carolina
Zahiri et al. (2014)			✓	FC	✓	✓		✓				Iran
Cardoso et al. (2015)			✓	FC	✓	✓		✓				Portugal
Guerrieroa et al. (2016)				PM/MC		✓						Italy
Zarrinpoor et al. (2017)			✓	FC		✓	✓	✓			BD	Baluchestan
Rastaghi et al. (2018)			✓	FC		✓	✓	✓			FOA	Iran
Intrevado (2019)			✓	FC	✓	✓						Canada
<u>Maternal healthcare facility location allocations</u>												
Jang and Lee (2019)		✓		MC		✓	✓		✓	✓		South Korea
Galvao et al. (2002)	✓			PM		-	✓$^{\Phi}$				LH	Rio-de-Janeiro
Galvao et al. (2006)	✓			PM		✓$^{\Psi}$	✓$^{\Phi}$				LH	Rio-de-Janeiro
Baray and Cliquet (2013)				PM/MC		-	-				LH	France
This work	✓		✓	FC	✓	✓	✓	✓	✓	✓	PSO,SA, ABD	India

Limitations: *ε Only health centres are capacitated, hospitals are uncapacitated.*

Ψ Only level 3 is capacitated.

Φ Referral is considered only for levels 2 to 3.

Legends: *SC- Set Covering; PM - p-median; MC - Maximum covering; FC - Fixed charge, AT - Approximation Technique, H - Heuristic, L - Lagrangean, AA - Average Approximation, GA - Genetic Algorithm, SA - Simulated Annealing, BD - Benders Decomposition, ABD – Accelerated Benders Decomposition, FOA - Fuzzy Optimization Approach, LH - Lagrangean Heuristic, LR -Lagrangean Relaxation.*

1.5 Present Work

1.5.1 Research scope

The challenges highlighted in the previous section desire serious attention of the health care planners. Mid-and-long-term strategic plans are required to establish new healthcare facilities, with upgradation and expansion of the existing healthcare facilities, for handling the increase in the future demand due to population growth. These plans need not only address the availability concern but also accessibility of the same within the economic and timely reach of MTBs originating from various locations. It might require revisiting of the current network of maternal healthcare facilities for upgrading and capacity building of existing facilities besides, determining the location of the new healthcare facilities in order to serve the MTBs at different locations with their number growing with time. By doing so the 'availability' and 'accessibility' issues concerning the maternal healthcare facilities can be properly addressed. It is this that spurred in undertaking the present research work. Figure 1.5 comprehensively shows the undertaken research framework related to the maternal healthcare system in India.

The scope of the thesis is limited to maternal healthcare only. The framework of the maternal healthcare planning undertaken in the present work assumes the establishment of separate and dedicated facilities for MTBs as the governments are focusing more on women health (Janani Suraksha Yojana, 2005; National Rural Health Mission, 2005; and Pradhan Mantri Surakshit Matritva Abhiyan, 2016) in an unprecedented manner. While planning the maternal healthcare system, the existing general healthcare system is not considered. These systems are already crowded and run short of doctors, etc. In planning of the exclusive maternal healthcare system, the existing general system are ignored believing that they will become more efficient and render better quality service for the other healthcare requirements.

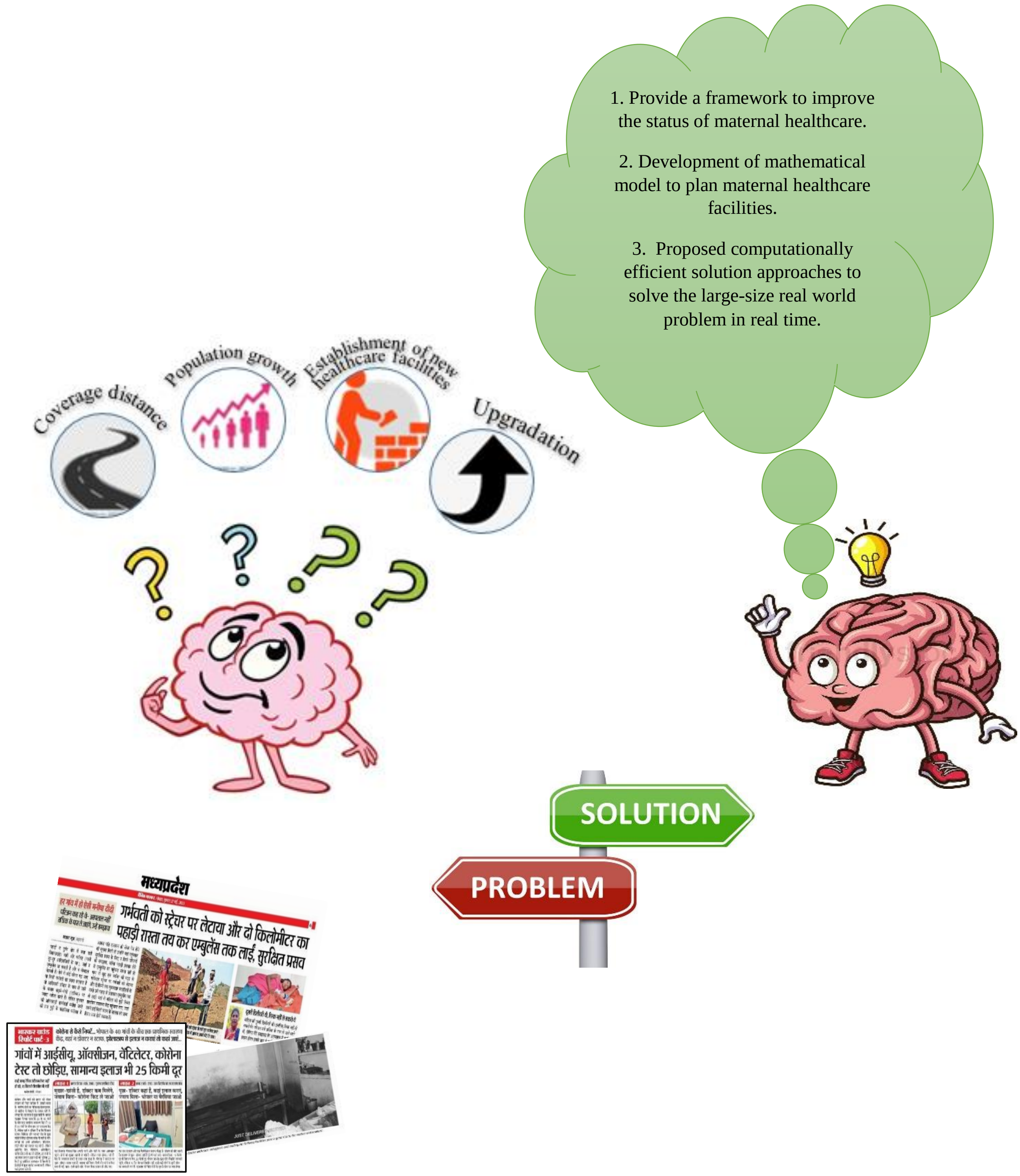

Figure 1.5: Undertaken research problem framework related to planning of maternal healthcare system in India

If the planning worked out suggests the establishment of a maternal healthcare facility at a location where it already exists, then the existing infrastructure will be provided to other hard-pressed and infrastructure-deprived medical services. Fixed and operating costs related to the establishment of healthcare facilities have been worked out on a daily basis, and so as the demand for the services rendered by these facilities. In India, health facilities are planned on the government land, and the cost is to be incurred only for the superstructure and the other amenities. Thus, the fixed cost incurred for establishing a facility at a location will depend upon its type and not the location. The same is also applicable to the up-gradation and operating cost of the facility.
In India, the government provides financial aid to pregnant women under various schemes, such as, Muthulakshmi Maternity Benefit Scheme and Pradhan Mantri Matru Vandana Yojana. Nearly every woman registers herself with the nearby Accredited Social Health Activist (ASHA) to get financial benefits through these schemes. Due to the rigorous government efforts through these schemes, it is easy to have a right estimate of the right number of pregnant women in a region. Currently, MTBs may have to cover a significantly large distance to reach the maternal healthcare units. It makes the accessibility issue further grave due to prevailing poor economic condition of the related MTBs in India. So the planning framework considers this aspect as well.

The proposed planning framework does not include any political consideration, but the economic ones besides consideration and all the stated service quality concerns. To have the optimized plan, mathematical modelling approach was resorted to. Given the nature of the underlying decision variables, the maternal healthcare facility location problem (MHFLP) can be mathematically modelled as a mixed-integer linear programming (MILP) problem. To solve small and medium-sized MHFLPs, traditional solution methodologies such as branch and bound can be used. However, these may be unable to discover a solution in a reasonable amount of time for large-scale real problems. MILP models for MHFLPs are NP-hard and highly combinatorial in nature. It means that the complexity will grow polynomially with the problem size, and the large-size problem may become intractable. In fact, in countries such as India, such planning problems are large scale problems owing to more than thousand villages in many administrative regions. For example, the Varanasi district of Uttar Pradesh state in India consists of 1333 villages. Seoni district of Madhya Pradesh state in India consists of 1593 villages, and the Kolar district of Karnataka state in India consists of 1809 villages (India Village Directory, 2021). To plan a maternal healthcare network in such a large region using MILP formulation will be a big challenge for the healthcare planners, particularly for those who look for a high-quality solution in a reasonable amount of time. This issue is addressed by adopting solution approaches that helped in providing good quality solutions in real-time.

1.5.2 Research objectives

This problem of planning the network of maternal healthcare facilities is basically a facility location-allocation problem. Looking into the nature of the problem, the present work has been devoted to the:

1. To study the various facility location models available in the literature and then plan the network of maternal healthcare facilities, from basic ones to neonatal ones, to address the challenges related to availability, accessibility, service quality and population growth.

2. To develop and propose a mathematical model for determining the optimal number and location of the capacitated and varied facilities within reach of MTBs and also for allocating

MTBs to these facilities while minimizing the cost of opening a new facility and cost of travel by the MTBs.

3. To carry out sensitivity analyses to see the impact of the change in various parameters, such as coverage distance, fixed cost, referral proportion, and capacity.

4. To determine the impact of demand variability on service quality and the number of healthcare facilities while penalizing allocations beyond the capacity of service facilities.

5. To develop and propose a strategic plan for locating and upgrading a hierarchical network of healthcare facilities in various time periods for maternal healthcare in India while minimizing the total cost that includes the cost of establishing a new facility, cost of upgrading the existing facilities, operating cost of the facilities, and cost of travel by the MTBs.

6. To develop effective and computationally efficient solution approaches to solve large scale real-world problems in real-time.

7. To plan the maternal healthcare facilities for the next 20 years for a region in India to show the applicability of the model.

1.6 Organization of the Thesis

The present research work is organized into five chapters of this thesis. A brief about the contents in these chapters is described below.

Chapter 1 introduces the maternal healthcare problem and outlines the challenges related to the same. The literature falling in the domain of healthcare facility location problems is presented and critically reviewed to identify the research gaps. This chapter also provides the scope for the research and also sets the objectives of the thesis.

In Chapter 2, a framework for planning the network of maternal healthcare facilities with full availability within reach is described. An illustrative example problem is presented to have a clear understanding of the model. Some valid inequalities and a three-stage sequential heuristic is proposed to solve the developed model. Sensitivity analyses is also performed to visualize the impact of the changes in various parameters.

In this Chapter 3, a framework for planning the network of maternal healthcare facilities with a penalty on normally varying demand is presented. The impact on service quality and the number of facilities is viewed due to normally varying demand and by imposing penalty on overburdening of the facilities. For solving the large scale problems, three metaheuristics, -namely particle swarm optimization, artificial bee colony and JAYA algorithm, are also presented to obtain a good quality solution in real-time.

In this Chapter 4, a framework for multi-period planning of maternal healthcare facilities considering population growth is described. Accelerated Benders decomposition, particle swarm optimization with local search and hybridized simulated annealing are each used to solve the large size problems. Additionally, the application of the model to plan maternal healthcare facilities for the next 20 years for a Tehsil in India is shown.

Chapter 5 concludes the current research work and also provides some meaningful managerial insights from this work. Finally, future research directions and possible extensions to this work are provided in this chapter.