

THE REFUGEE CAMP MANAGEMENT: A GENERAL FRAMEWORK AND CLEAN WATER NETWORK DESIGN

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE
OF BILKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF
MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING

By
Elif Akkaya
January 2017

The Refugee Camp Management: A General Framework and Clean
Water Network Design

By Elif Akkaya

January 2017

We certify that we have read this thesis and that in our opinion it is fully adequate,
in scope and in quality, as a thesis for the degree of Master of Science.

Bahar Y. Kara (Advisor)

Özlem Karsu (Co-Advisor)

Ayşe Selin Kocaman

Melih Çelik

Approved for the Graduate School of Engineering and Science:

Ezhan Karaşan
Director of the Graduate School

ABSTRACT

THE REFUGEE CAMP MANAGEMENT: A GENERAL FRAMEWORK AND CLEAN WATER NETWORK DESIGN

Elif Akkaya

M.S. in Industrial Engineering

Advisor: Bahar Y. Kara

Co-Advisor: Özlem Karsu

January 2017

Motivated by the increasing need to provide support to refugees, which remains as a pressing issue in the agenda of many countries, we consider the refugee camp management problem. It is of utmost importance that asylum-providing countries co-operate with the Non-Governmental Organizations (NGOs) while managing the process and use the resources efficiently and effectively. The Refugee crisis is one of the challenges of today's world mainly due to the difficulties such as geographical discrepancies and unknown duration of refugee camps.

In the first part of the thesis (Chapter 2), we consider the refugee camp management process with an Operations Research (OR) perspective and provide a framework. In the proposed framework, the overall refugee camp management problem is first categorized into two main phases: the establishment phase, which consists of one-time decisions such as infrastructure design; and the administration phase, which focuses on routine decisions that are taken on a periodic basis like aid distribution. We then detail each phase via sub categories and link each decision made in these sub categories with an appropriate decision problem from the OR literature. The proposed framework is aimed to be general enough to cover the problems that might arise in different geographies.

In the second part of the thesis, the water network design problem encountered in establishment phase of refugee camps is considered. We propose single and bi-objective models that determine the locations of water well and water distribution units (WDUs), and design the general network structure (transmission pipes). As objective functions; total cost as a function of pipe length and total walking distance of refugees to the closest water source are utilized. The minimal

requirements defined by various NGOs are incorporated into the models. One of them is ensuring that the distance between a tent and its closest WDU should be below a certain threshold, which is imposed on the models as a covering constraint. The data set acquired from Gaziantep refugee camp in Turkey is utilized when solving the models.

We solve the single objective models using CPLEX. While solving bi-objective models, the epsilon constraint approach is applied in order to find the optimal Pareto frontier. In our computational experiments, we observed that for smaller threshold values, solution times increase in an exponential manner. Thus, we modify the non-dominated sorting genetic algorithm (NSGA-II) and use it to solve such problems. The quality of the Pareto solutions acquired by NSGA-II and the epsilon constraint method are assessed via performance measures defined in the literature.

Keywords: Refugee camps, process management, clean water distribution network design.

ÖZET

MÜLTECI KAMPI YÖNETİMİ: SÜREÇ ANALİZİ VE KULLANIM SUYU DAĞITIM AĞI TASARIMI

Elif Akkaya

Endüstri Mühendisliği, Yüksek Lisans

Tez Danışmanı: Bahar Y. Kara

Eş-Tez Danışmanı: Özlem Karsu

Ocak 2017

Mülteci kampları, savaş gibi zaruretler sebebiyle bir ülkeye sığınan mültecilere barınmaları amacıyla sağlanmaktadır. Sığınma sağlayan ülkelerin, Sivil Toplum Kuruluşları (STKlar) ile işbirliği halinde, süreci doğru yönetmesi ve kaynakları etkili kullanması, büyük bir önem arz etmektedir. Savaşın ne kadar süreceğinin bilinmemesi, sığınma sağlayan ülkelerin ve STKların sınırlı kaynaklara sahip olması ve günden güne artan mülteci sayısı, bu problemin zor bir problem olmasının başlıca nedenlerindendir. Tezin ilk kısmında (Bölüm 2), genel olarak mülteci kamplarının kurulumu ve işletimi süreçlerini Yöneylem Araştırması yöntemleri kullanılarak incelemek amaçlanmıştır. Yapılan çalışmanın, farklı coğrafyalarda meydana gelebilecek problemleri ele alacak bir genellikte oluşturulması hedeflenmiştir.

Tezin diğer kısmında ise, mülteci kamplarının kurulum süreçlerinden biri olan kullanım suyu dağıtım ağının çok amaçlı optimizasyonu incelenmiştir. Su dağıtım noktalarının ve ağın tasarımına karar veren tek ve iki amaçlı matematiksel modeller geliştirilmiştir. Amaç fonksiyonları olarak toplam ağ uzunluğunu ve su dağıtım noktalarına toplam yürüme mesafesini en küçükleme kullanılmıştır. Çeşitli STKlar tarafından belirlenen minimal gereklilikler dikkate alınmış ve her çadırın en yakın su dağıtım noktasına olan yürüme mesafesinin belirli bir eşik değerinden küçük olması gerekliliği kısıtlara yansıtılmıştır. İki amaçlı modelleri çözdürmek ve Pareto çözüm kümesini bulabilmek için epsilon kısıtı metodu kullanılmıştır. Küçük eşik değerlerinde modeller en iyi çözüm makul sürelerde bulunamadığı için, Baskın Sıralı Genetik Algoritma-II (BSGA-II) kullanılmıştır. BSGA-II metoduyla elde edilen çözümlerin kalitesi, literatürde tanımlanan performans ölçüleriyle değerlendirilmiştir.

Anahtar sözcükler: Mülteci kampları, süreç analizi, su dağıtım ağı tasarımı.

Acknowledgement

First of all, I would like to thank my advisor Prof. Bahar Y. Kara and my co-advisor Asst. Prof. Özlem Karsu for their invaluable support, understanding, and guidance during my graduate study.

I am also very grateful to Asst. Prof. Dr. Melih Çelik and Asst. Prof. Ayşe Selin Kocaman for accepting to read and review this thesis. Their comments and suggestions have been invaluable.

I would like to thank my dearest EA307-officemates for their moral support and companionship, countless coffee breaks, puzzle times, and endless fun.

I would like to express my deepest gratitude to Betül Çoban for her endless support and patience she has shown to all of my questions for the last two years as an old colleague and best friend. Also, I want to thank my dearest sisters Yasemin Yılmaz, Yeliz Gökçer, Hümeysra Çelik and Beril Uslu for being with me all the time, and for making my graduate life bearable and enjoyable.

Above all, I would like to express my profound acknowledgement to my family, my mother Havva Akkaya, my father İsmail Akkaya and my brother Furkan Akkaya for their unconditional love, moral support, motivation and trust at all stages of my life. I owe everything that I have achieved to my family.

To my mother...

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Chapter 1

Introduction

Because of the increasing need to provide support to refugees, which remains as a pressing issue in the agenda of many countries, it is crucial to use the resources efficiently and effectively. However, studies related to refugee crisis in the OR literature is scarce.

This thesis is composed of two main parts; the analysis of refugee camp management problem in order to develop a general framework, and one of the sub-problems defined during the first analysis: the water distribution network design problem in refugee camps.

In Chapter 2, we study all aspects of the refugee camp management problem from the most strategic level concerning the location decision to daily decisions in the administrative level. We categorised our analysis into two: the establishment phase, where we focus on the main decisions regarding the establishment of the refugee camps, and the administration phase, where we study the tactical and operational issues for the everyday life at refugee camps. Firstly, we analyze the establishment phase in detail. The output of this analysis will provide the final camp layout, which is the main input of the administrative phase. We aim to define the sub-problems of each phase in detailed manner and link these problems with the OR literature.

In the following chapters, one of the sub-problems of the establishment phase, clean water infrastructure design problem in refugee camps, is discussed in detail. The most substantial resource that should be provided to refugees is water. Due to the long-servicing feature of the refugee camps, water infrastructure should be designed to fulfill the minimum requirements that United Nations High Commissioner for Refugees (UNHCR) [6] or The Sphere Project [7] have defined. Geographical and financial constraints shape the design of water network according to the necessities of the region. For instance, if local water network is available, then it is extended and used as a water source of the camp. However if local water network is not accessible or the region is dry, water wells are drilled in order to satisfy the water demand of the camp. Note that possible locations of water wells depend heavily on the underground water availability as a well can only be drilled at a point if there is water underneath.

Water infrastructure network design problem in refugee camps is quite different from municipal water network design [8]. One of the major differences between these two problems is that: although water should be accessible in every demand point in a residential area, this is not necessarily the case in a refugee camp, i.e. water taps may not be located in every tent. In general, in camps, water is supplied to common use areas such as kitchens, restrooms, baths, and WDUs.

In camps where each tent does not have its own water tap, WDUs should be close enough to each tent. UNHCR and The Sphere project define minimum requirements regarding the access to clean water. For example, according to Handbook for Emergencies by UNHCR, maximum distance between a demand point (tent) and its closest WDU cannot be more than 100 meters [6]. Such constraints should also be considered while designing the infrastructure.

In this study, we propose mathematical models that determine the locations of a water well and WDUs and the design of water network structure, respecting the threshold distance. In our initial models, we assume that there is a fixed water well in camp area. We formulate two single objective models that minimize the total pipe length and total walking distance, respectively. Next, the assumption that the well location is fixed is relaxed and two single objective models are

developed which also choose the location of well among the candidate locations. Then, bi-objective extensions of the models are considered which minimizes total walking distance from each tent to its nearest WDU alongside total pipe length.

The thesis is organised as follows: in Chapter 2, we explain the refugee camp management problem. We firstly highlight the Syrian refugee crisis and the current situation in the world followed by more detailed overview of situation in Turkey. Then, we provide the framework that we propose for refugee camp management accompanied with a visualized overview of all sub-systems. We discuss the details and daily life challenges of the establishment and administrative phases. While detailing the refugee camp management problems, we highlight various OR problems that are relevant to link the practise with the literature.

Chapter 3 contains the problem definition, assumptions and the literature review. In Chapter 4, the single and bi-objective mathematical models that address the problem are developed. We first assume that the location of well is fixed, and we model this case for both objectives, separately. Similarly, we also formulate the case that location of the well is to be determined among the set of candidate well locations. The single-objective models are developed to provide a basis to the bi-objective models. Finally, we formulate the bi-objective models for fixed and variable well location cases, respectively.

The exact and heuristic solution methodologies proposed for bi-objective models are explained in Chapter 5. To find the exact Pareto solutions of bi-objective models, we utilize the epsilon constraint method. For smaller threshold distances, the models are harder to solve and solution times increase significantly. Thus we develop an adaptation of one of the best-performing multi-objective combinatorial optimization metaheuristics: NSGA-II [9]. In order to assess the quality of exact and approximate Pareto solutions returned by NSGA-II, we use some performance measures from the literature.

In Chapter 6, data sets and instances are created in order to test the behaviour of the proposed solution methodologies. Using the data sets defined in Chapter 6, computational analyses of single-objective and bi-objective mathematical models

are presented in Chapters 7 and 8, respectively. Additionally, Chapter 8 includes the results of NSGA-II and assessments of the performance measures. The thesis ends with concluding remarks in Chapter 9.

Chapter 2

The Refugee Camp Management Problem: A General Framework

The refugee crisis has multiple dimensions, one of which is refugee camp management. The refugee camp management problem is very challenging due to the difficulties such as geographical discrepancies and unknown duration of refugee camps. However, few studies have been conducted on the scope of refugee camp management in the OR literature so far.

In this chapter of the thesis, we study all aspects of the refugee camp management problem from the most strategic level concerning the location decision to daily decisions in the administrative level. We categorised our analysis into two: the establishment phase, where we focus on the main decisions regarding the establishment of the refugee camps, and the administration phase, where we study the tactical and operational issues for the everyday life at refugee camps. We first explain the Syrian refugee crisis in the world and in Turkey, then consider the establishment phase in detail. The output of this analysis will provide the final camp layout, which is the main input of the administrative phase.

2.1 Syrian Refugee Crisis

2.1.1 Current Situation in the World

A refugee is “someone who has been forced to flee his or her country because of persecution, war, or violence” according to the definition of UNHCR [10]. Additionally, an internally displaced person (IDP) is “a person who has been forced to flee his or her home for the same reason as a refugee, but remains in his or her own country and has not crossed an international border.” In terms of structural features; the refugee and IDP issues can be analyzed under the same headline [11].

Hosting asylum-seekers who are obligated to flee their homes due to civil war or public war, is one of the oldest problems in the history of mankind. “Everyone has the right to seek and to enjoy in other countries asylum from persecution.” according to UNHCR [12]. Countries of asylum, collaborating with NGOs, should plan the whole process correctly and use the resources efficiently in order to ensure that refugees can live in a manner compatible with human dignity. The refugee problem is one of the most challenging humanitarian problems due to such reasons as uncertain duration of war, limited resources and the steadily increasing number of refugees.

Today, the world is facing one of the biggest refugee crises. The Syrian civil war began in 2011 when thousands of Syrian citizens fled across the border to neighboring Turkey, Lebanon, Jordan and Iraq. The list of the number of Syrian refugees in neighboring countries, as of 2016, is given in Table 2.1 [13].

Table 2.1: The number of refugees in neighboring countries (in 2016)

Country	Number of Syrian Refugees
Turkey	2,733,655
Lebanon	1,033,513
Jordan	656,400
Iraq	225,455
Egypt	114,911

Some of the refugees have even migrated beyond countries in Europe, North Africa and the Caucasus. Asylum appeals of Syrian refugees in Europe have surged in 2015. The infographic in Figure 2.1 demonstrates the number of Syrian refugees in neighboring countries of Syria and European countries from April 2011 to October 2015. It shows that countries such as Sweden, the Netherlands, Algeria, Austria and Greece each has accepted more than 10,000 Syrian refugees.

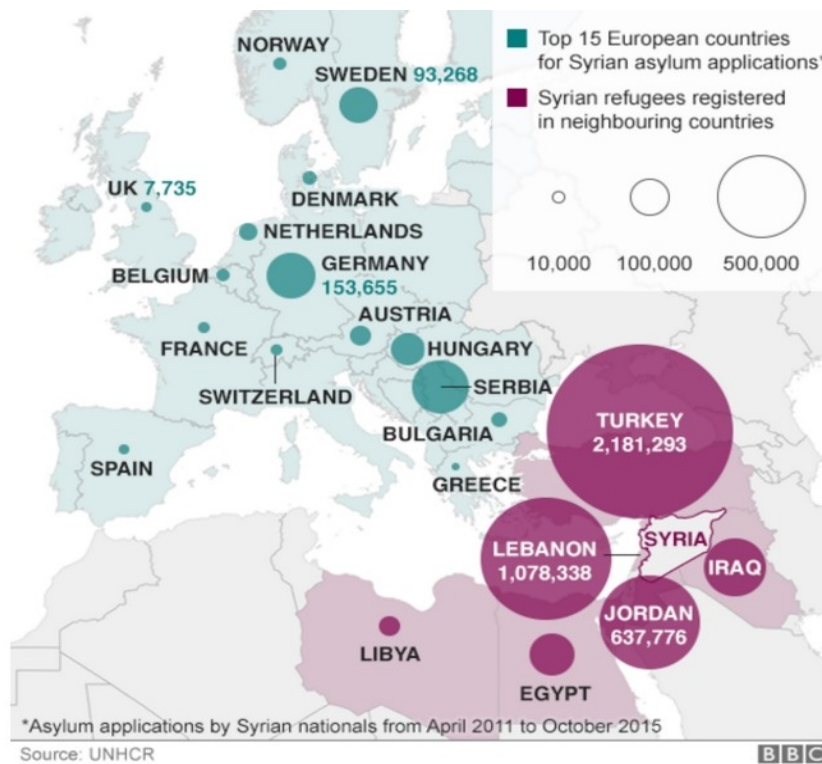


Figure 2.1: Syrian refugees in neighboring countries and Europe [1]

However, these numbers are not certain, as some refugees may have passed through borders or arrived by sea undetected. Germany has received the highest number of Syrian refugee applications of Europe with more than 331,000 by the end of October 2015. Providing asylum for more than 2 million refugees, Turkey accommodates three times the number of refugees in Europe as of 2015. Figure 2.1 shows that the majority of Syrian refugees resides in Turkey.

2.1.2 Refugees in Turkey

Since the beginning of the Syrian civil war in 2011, Turkey has faced an intensive Syrian refugee crisis. According to official information from the UNHCR, Turkey hosts roughly 60% of the Syrian refugees in the world [14].

Besides Syrian refugees, Turkey also witnessed an unprecedented increase in asylum applications from Afghans, Iraqis and Iranians since 2014 [15]. According to the UNHCR, by July 2016, Iraqi and Afghan refugees and asylum seekers were estimated approximately 124,298 and 110,764 respectively [2].

Being a country prone to many different kinds of disasters, Turkey established The Disaster and Emergency Management Presidency of Turkey (AFAD) in 2009 in order to take necessary measures for prevalent emergency management. AFAD conducts pre-disaster actions such as preparedness and risk management, prevents the effects of disasters, minimizes disaster-related damages, plans and coordinates post-disaster processes such as recovery and reconstruction. AFAD reports to the Turkish Prime Ministry and it is the sole authorized institution in disaster and emergency situations. Notwithstanding its unique position on disasters and emergencies, AFAD coordinates with a range of government institutions such as the Turkish General Staff, the ministries of Foreign Affairs, Interior, Health, National Education, Forestry and Water Affairs, among others. It also promotes cooperation among private institutions, (I)NGOs, UN agencies and Turkish Red Crescent (TRC), depending on the nature and severity of individual cases [16]. As an example, providing shelter areas to Syrian refugees is AFAD's responsibility [17].

TRC works in close collaboration with AFAD on a range of issues, one of which is the Syrian Humanitarian Relief Operation. Before the establishment of AFAD in 2009, TRC was one of the main supporting organizations in Turkey and it is one of the main solution partners, working on relief operations for long periods of time and has many years of experience. TRC has various responsibilities in different areas including blood services, national disaster management, international programs and social services. Within the scope of Syrian Humanitarian Relief

Operation, TRC has vast duties and responsibilities, which can be categorized into two main groups based on the location of the refugees it serves. For Syrian refugees who live in the camps, TRC has been responsible for the fulfilment and distribution of basic humanitarian needs (i.e. tents, food, hygiene and medical supplies etc.) supporting the workforce (i.e. educators, health officers etc.) and procurement of side missions such as transportation and psychosocial support services.

The activities stated above are carried out in the 25 refugee camps established in 10 different cities, in Turkey. 17 of 25 refugee camps are in the form of tent city, whereas 8 of them are container cities. The refugee camps host an estimated 254,497 people. The spread of the refugee camps in Turkey can be seen on the map given Figure 2.2.

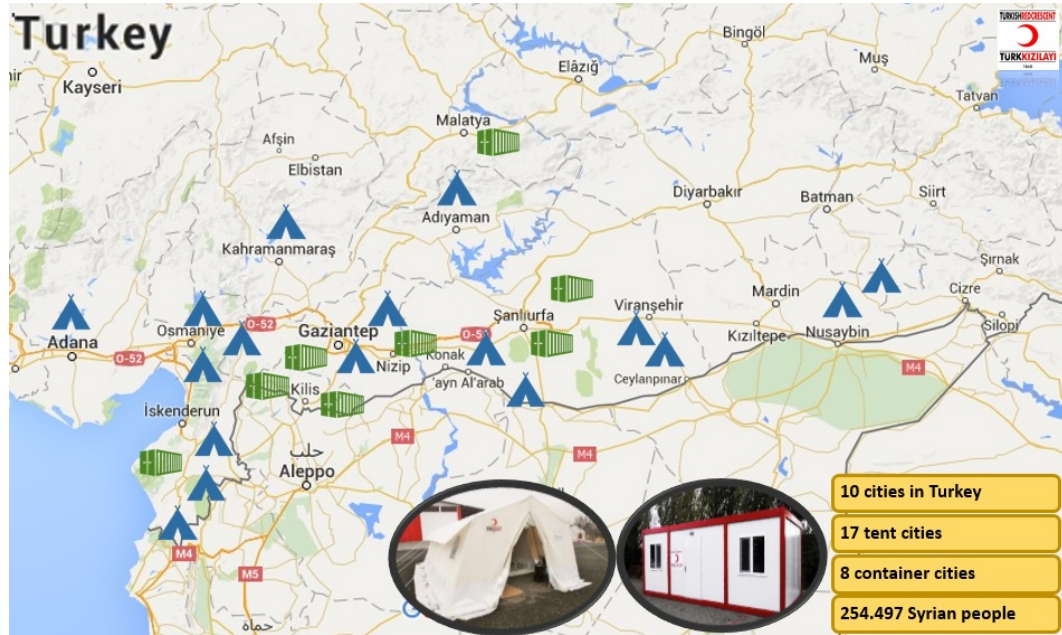


Figure 2.2: Refugee Camps in Turkey, as of October 2016 [2]

TRC has also been performing border aids to Syrian people who are still on the Syrian side of the border via Border Aid Centers in Hatay, Gaziantep, Şanlıurfa and Kilis [18].

2.2 Refugee Camp Management

We define refugee camp management as the entire process which begins with deciding to establish a refugee camp and continues as long as the conflict remains. We analyse refugee camp management in two phases: establishment and administration. Establishment process involves strategical and one-time decisions, and administrative issues involve tactical and operational decisions that require periodical planning as long as a refugee camp serves. The general overview of refugee camp management can be seen in Figure 2.3.

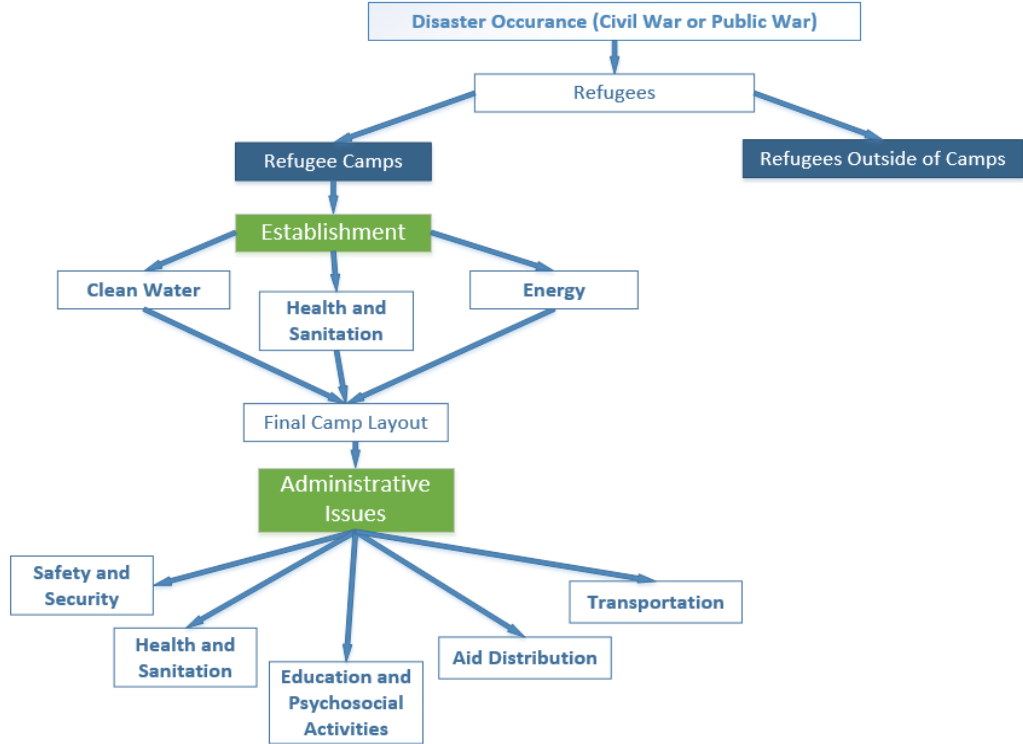


Figure 2.3: Overview of Refugee Camp Management Framework

Establishment phase includes infrastructure design for clean water, health and sanitation and energy. These decisions lead to the final layout of the camp. Once the camp is set up and refugees start to live in it, administrative phase begins. Within the scope of administrative issues; safety and security, health and sanitation, aid distribution, transportation services, education and psycho-social

activities are planned and conducted.

It is noticeable in the literature that research related to refugee camp management is scarce. The limited number of published studies regarding this topic are mainly about the establishment phase of a refugee camp. Mostly in these studies, certain standards are stated, such as the minimum distance that must be kept between each pair of shelter or the maximum distance allowed between a refugee residential area and a water distribution point [11].

The Sphere Project [7] and UNHCR [6] declare the minimal requirements during the construction process. Refugee Camp Planning and Construction Handbook is published by Department of the US Air Force [19], which constitutes another guide on the construction processes of refugee camps. There are also review studies which compare different minimal requirements in the literature, such as studies of Kennedy [11] and Department of the US Air Force [19].

One of the biggest challenges in refugee camp management is the fact that, while establishing camps in various regions, the necessities of the different geographies should be considered. For instance, in the regions where local energy infrastructure is accessible, energy can be provided from the infrastructure. When this is not possible, off-grid energy sources should be used as a supplier. To take another example, in the regions where water problems exist such as Somalia [4], wells must be constructed. In other parts where water infrastructure is accessible, there is not such a need for wells. In addition to these, there could also be some cases of contagious diseases or insect invasions, specific to the location. The examples for different cases in different regions can be multiplied.

The second crucial property of refugee camps is that they may have to serve for many years, since the conflict may remain for a long period. In history, there are many examples of refugee camps that provide service for more than 20 years such as camps established in Bosnia and Herzegovina, Sudan and Afghanistan [20]. The long-lasting nature of refugee crises necessitates the detailed planning and the consideration of all possible cases. For these reasons, administrative issues have as much importance as the camp establishment phase.

Besides the studies mentioned above on the refugee camp establishment phase, studies on the administrative process are even more limited. A few studies specific to refugee camp administration is addressed in Section 5. Although the administrative process involves decisions which can be made using OR tools, the problem of refugee camp administration has not been studied with an OR point of view in the literature.

In this study, we aim to discuss the main processes related to management of a refugee camp with an OR point of view. Integrating TRC's know-how with OR perspective, we manage to visualize these processes and their interaction (see Figure 2.3).

2.3 Refugee Camp Establishment Phase

Once the decision of building a camp for refugees is made, the first unknown is the location of the camp. At the very beginning, areas at an adequate size for the camp are determined. The ground study and infrastructure works of the sites where the camps will be established are performed. The candidate camp locations should be selected in convenient areas for connecting electricity, water and sewage networks to the city network, if possible. If the areas have no or inadequate electricity and water infrastructure, the necessary infrastructure works should be performed.

Camps should be established at the sites that are suitable for settlement and close to existing social facilities, and where the refugees feel safe and comfortable and can benefit effectively and efficiently from the provided services. For instance, the camps should not be established close to the border and potentially dangerous areas [3].

Choosing the camp location is a special type of multiple-criteria decision making problem [21]. Information on the candidate camp locations such as distances to roads or hospitals, local energy and water network availability and other factors (e.g. weather conditions or ownership of the land) is used in determining and evaluating the candidate camp locations.

After the designation of the location, the establishment process can commence and issues such as *Water*, *Health and Sanitation* and *Energy* should be considered. A detailed overview of refugee camp establishment phase can be seen in Figure 2.4. After determining the Water, Health and Sanitation and Energy infrastructure, camp layout takes its final form. These issues are explained in a more detailed manner in the following sub sections.

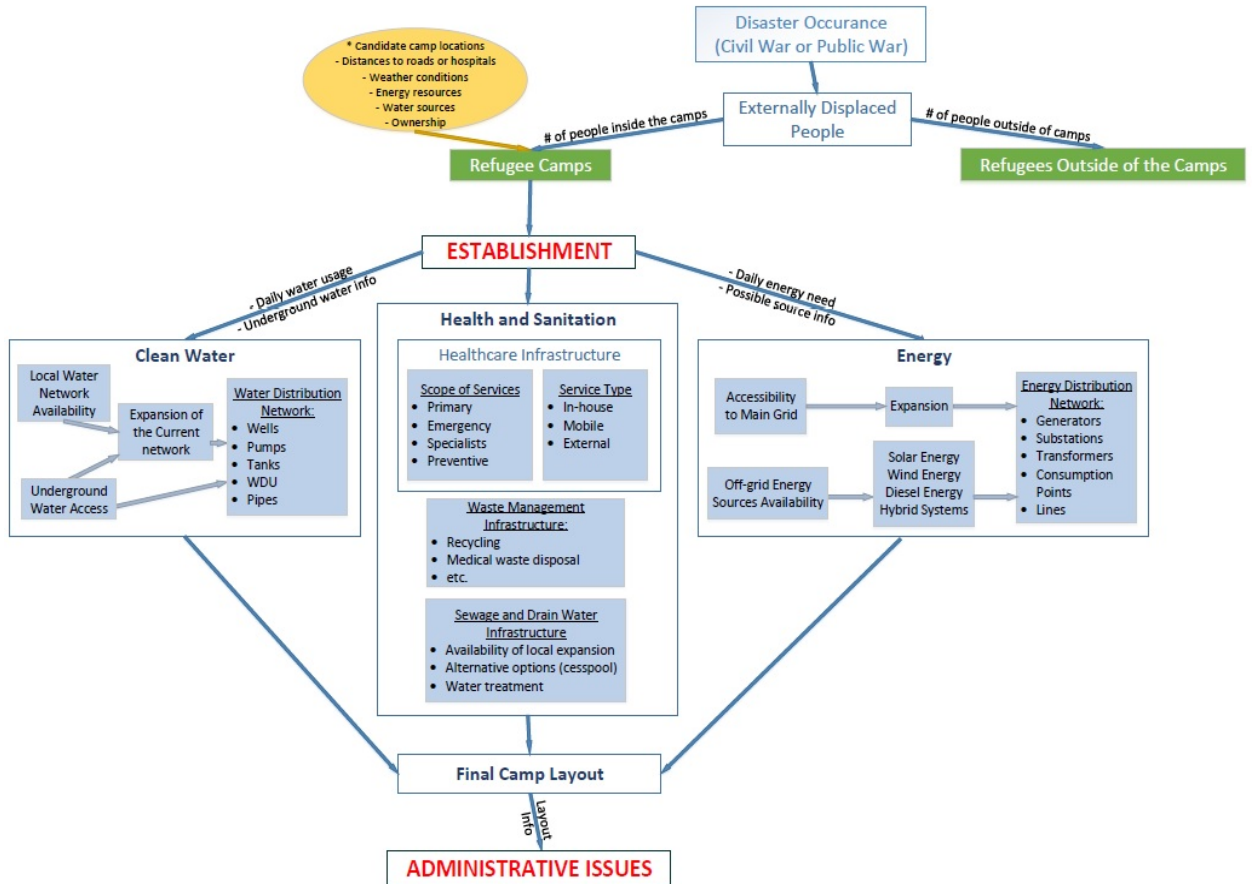


Figure 2.4: Detailed Overview of Refugee Camp Establishment

2.3.1 Clean Water Infrastructure Design

In order to determine the water distribution infrastructure of the camp, firstly, information on the demand and supply of water such as estimated daily water usage and underground water availability is required. While designing the infrastructure, geographical features such as pressure, height and the slope of land should also be considered.

According to local water network and underground water availability information, it will be determined whether water need will be satisfied by water wells or local water infrastructure. If local water network is available, water can be provided by extending it. However, if public water network is not accessible from a refugee camp, there is no spring water at reachable distance, or camp area is on a dry zone, then well is the only water source for the camp. For instance, in the refugee camps in Turkey, water needs are met with local water supplies, because local water network is expendable. But in Somalia refugee camp [4], water is supplied by water wells because there is no local water network accessible and the region is arid.

In the literature, there have been a few studies related to refugee camp water consumption and treatment. Roberts et al. [22] try various methods to keep the drinking-water clean in the Mozambique refugee camp. Cronin et al. [23] emphasize the importance of providing sufficient amount of water containers to the camps in order to store the right amount of water. It is also mentioned that sufficient amount of water supplied helps in prevention of epidemic diseases such as diarrhea, and cholera. Related to the provision of water in sufficient quantity and quality, minimum standards and indicators of UNHCR and the Sphere Project were also compared in this study.

In the water network design problem, the main decisions that should be made are where to locate water distribution units and how to design water network. If water wells are used, locations of water wells will also depend on the underground water information. While locating water distribution units, minimal requirements of The Sphere Project [7] or Handbook for Emergencies [6] should be considered.

Water taps, toilets, bathrooms and kitchens are located in the camp according to the water network design. In some situations, water tanks and engines may also be needed. The overall network involves clean water and sewage network designs. These two networks are interrelated, hence their design processes should be considered and conducted simultaneously. Geographical and financial constraints and minimum requirements shape the general design of a camp. Therefore, camps at different locations are designed in different ways. For instance, in the IDP camp in Somalia, water requirement is met with common use water taps [4] and there is one shared kitchen in the camp. However, water and kitchen is provided in each shelter in the Syrian refugee camp, Kilis, Turkey [24].

As stated before, clean water distribution problem will be different based on the local infrastructure availability. That is, the problem can be considered as an urban network design/extension problem if the local infrastructure is available, or it can be considered as a stand alone network design problem including its own source and distribution decisions if the local infrastructure is not available or is insufficient. In both cases, the underlying OR problem is a specialized network flow problem which will also include additional constraints due to the application dynamics. The locations and the demand structures of kitchens, laundries, shelters and criteria to be met (for example having a tap at each shelter or having one water distribution unit for say 20 shelters) will shape the exact problem to be considered.

2.3.2 Energy Infrastructure Design

Another important topic that should be analyzed before establishing the camp is energy infrastructure design. Electrical power should be used for different purposes such as security lighting, access lighting and operating water pumps around the camp. If time and funds permit, electrical power can then be provided to individual shelters. Providing adequate energy to every refugee helps them cook for themselves, gather with friends and visit the bathroom more safely and easily. This is especially important for women and children.

Local energy network availability and geographical features are important factors while determining the source of energy. It should be ascertained whether a local energy network is accessible or off-grid energy systems should be used. Solar and wind power and generators can be given as examples of off-grid energy resources. Once energy source is determined, the electric power distribution of the refugee camp is conducted. Energy network design involves decisions on the location, type and capacity of energy generation and storage facilities and location of demand points. A demand point can be a residential tent or a common use area. These type of decisions also affect final layout of the camp [19].

Salehin et al. [25] aim at conceptualizing an Emergency Energy Module which provides electrical energy to satisfy the energy demand of a refugee or a relief camp and the aid workers for a long term. As a case study, a refugee camp near Chad-Sudan border has been investigated. Franceschi et al. [26] concentrate on off-grid power and describe different types of energy systems used in humanitarian activities. The authors compare different technology solutions that exist for emergency relief activities, refugee camp activities and micro-grid development.

Different energy sources are possible such as solar, diesel or wind energy. The energy system which is planned to be used in Azraq refugee camp (a Syrian refugee camp of UNHCR in Jordan) can be an example of a solar-based energy system [27]. A solar farm will be built to provide energy mainly to refugee camp and any access will be used by the grid. This project will also provide financial assistance to refugees as they are going to be employed in the construction process.

Energy is not only used for lighting, but also for heating and cooking. Coal or electrical energy can be used for residential heating. For cooking, bottled gas or similar resources can be used. An interesting example of cooking gas usage in camps, is seen in Bangladesh Nayapara refugee camp, where cooking gas is produced by extracting biogas. In this camp, there are many residents and thus waste management becomes a major challenge. The developed system extracts biogas from waste and transfers it through a pipe to kitchens for cooking. By this way, a large quantity of biological waste is turned into cooking gas for refugees [27].

Similar to the clean water network design case, the energy network design problem will also be differently shaped depending on the local infrastructure availability. It can again be considered as a network expansion problem with decisions including additional generators (types being determined by local infrastructure), substations, transmission network; or as stand-alone energy system planning problem with similar decisions on generators (type, capacity, etc.), substations and storage. Especially in the off-grid structure, sustainable solutions can also be applicable, which brings another venue of OR methodology applications with its own challenges and dynamics.

2.3.3 Health and Sanitation

The water and energy sub-modules of the establishment phase that we have discussed mainly include distributing somewhat continuous resources to the usage points. Therefore, these two issues are crucial in the establishment phase. Once the networks are designed in a sufficient way, they will not bring significant operational challenges other than routine maintenance operations. However, health and sanitation issue is crucial in both establishment and operational phases. We will discuss the one-time decisions in this section, which will be followed by detailed operational decisions in Section 2.5.2.

Under the health and sanitation headline, the main topics to be considered include healthcare facility location and design, waste management infrastructure and sewage and drain water infrastructure.

There are three ways of providing healthcare service in a refugee camp which are in-house, mobile and external. In the in-house option, health centers (poly-clinics and subspecialty clinics) are set up into the camp. In this case, the most important factors are the capacity and the scope of service of the healthcare facility. Capacity will be determined based on factors such as presence of hospitals nearby, financial constraints and the number of refugees in the camp. There are four main categories of scope of health services which are emergency, primary

healthcare, preventive and specialized care. It should also be decided which services will be provided and to what extent.

To ensure adequate hygiene level and to prevent any health related issues such as epidemics, waste management and sewage infrastructure are crucial. The waste management process can even start from debris cleaning, which may be an issue at the camps located in conflict zones, and will include classical municipal waste management issues such as land sites for wild dumping, recycling options, bone grinding, pest control and handling medical waste, which should definitely be managed apart from the municipal waste.

In the literature, Klumpp et al. [28] study waste management and recycling of refugee camps. They provide a classification of waste according to different type of disasters including refugee crisis and they proposed some solutions to re-use of waste. Garfi et al. [29] analyze waste management of a Saharawi refugee camp using the method of analytical hierarchy process. Waste management of refugee camps and municipal waste management are somewhat similar to each other. Thus, studies addressing the municipal waste management also can be good references for the refugee camp waste management problem [30].

Appropriate management of sewage and drain water is important for the sake of health and sanitation. Similar to energy and water network, availability of a local infrastructure will determine the problem specifics. The overall sewage and drain water of the camp may be embedded to the municipal networks, if exists, or the camp management should address the problem by considering cesspools and water treatment points, and any other relevant units.

From an OR point of view, problems encountered in health and sanitation are mainly variants of location problems, whereas the sewage and drain network design leads to variations of network flow problems. Of course the criteria and constraints to be considered will be different for health and waste management problems. For healthcare service provision, the main decisions in the establishment phase will include locations and the scales of the facilities to be located while ensuring fair and easy access. On the contrary, in waste management the

service should be provided in such a way that the dump sites and any hazardous facilities should not endanger the daily life and this triggers the anti-closeness criteria. Again, all these problems are of multi criteria nature, involving potentially conflicting criteria. To take another example, locating a dump site would include concerns on distance and fairness. The site should not be too far away from the camp, as otherwise it would lead to high transportation costs. However, as this is an obnoxious facility location problem, one should also ensure that at least a certain level of distance is kept between any residential point and the facility. Moreover, there are fairness issues to be considered: a solution subjecting some population groups to much higher risks than the others would not be acceptable.

2.4 Final Camp Layout

After planning the *Clean Water*, *Health and Sanitation* and *Energy* infrastructure during the establishment phase, final camp layout can be shaped accordingly with the locations of all the facilities that would be included in these networks.

In addition to the infrastructural facilities outlined in previous section, there are other types of facilities which are essential for the daily life of refugees in a camp. These types of facilities include but not limited to kitchen and cafeteria, WC and baths, laundry and dish-washing units. Considering the fact that refugee camps may last long, refugee camp management should also consider public services which at least should include healthcare, education and security facilities. In addition to these, religious facilities, social activity centers (i.e. playgrounds, sports fields, multi-purpose areas, TV/internet halls), administrative facilities (i.e. interpreting offices, registration etc.) can also be considered. A commercial zone/plaza may even be planned which may include grocery stores, pharmacies, banks and/or ATMs, etc. [3]. An overall list of the necessary facilities can be seen in Figure 2.5.

Shelters	Kitchen & Cafeteria	Social Activity Centers	Laundry/ Dishwashing	WC/Baths	Administrative Facilities
Healthcare Facilities	Safety & Security	Transportation Facilities	Education Facilities	Religious Facilities	Commercial Facilities

Figure 2.5: Final Camp Facilities

A variety of guidelines have been published in the literature to assist the decision makers in shelter and site planning with regards to design and the minimal requirements including number of shelters and facilities and the distances in between ([31],[6],[7]). For example, settlement areas should be planned in a way to allocate at least 45 m^2 of space per person including infrastructure, social facilities, and shelter areas, according to The Sphere Project [7]. On the average, one shelter should be supplied for a family. Refugees in these camps live there for a long time, hence it is important to ensure that at least minimum standards of a normal daily life can be met. Besides, this is crucial in terms of ensuring privacy and family life ([7],[6]).

As the camps may serve for long periods of time, safety measures have to be taken and a sustainable safety system should be planned. Police and gendarmerie departments should be located in checkpoints and entrances to ensure the safety of refugees. The fire-fighting department and system should be planned in a way to enable the most rapid access to all points in case of a fire. Thus, while designing camp layout and water supply network, fire fighting water supply points should also be considered. Figure 2.6 gives an example from Ceylanpinar tent city in Sanliurfa, Turkey [3].



Figure 2.6: Fire fighting unit in Ceylanpinar tent city in Sanliurfa, Turkey [3]

The problem of locating hydrants is considered in the urban OR literature as the maximal covering location problem [32] and thus maximal covering references could be utilized in designing the fire-fighting system of the camps. The other aspects of the final camp layout lead to various applications of classical location problems in the OR literature. Placing the facilities while considering their mutual relationships and obeying minimal/maximal requirements can be recognised as an application of layout problems of the OR literature.

2.5 Refugee Camp Administration

As stated before, administrative processes of a refugee camp have not received enough attention in the literature. McAdam [33] studies the administration of refugee camps within a limited scope and focuses on issues such as how to select management staff and other personnel of refugee camps. Cosgrave [34] reviews the nature of decision making in emergencies and then suggests a simplified decision process model for emergency managers, exemplifying it with refugee emergencies. Cuny [35] analyzes refugee camp planning and details management process under four titles: physical, social, health and administrative factors. Under the sub-title of physical factors, Cuny discusses issues related to site selection and planning. In the administrative factors, he analyzes how a refugee camp should be run.

In this study, management of a refugee camp is considered as a whole. Therefore besides establishment phase, the administrative issues of a refugee camp are also analyzed under five sub-titles as *Safety and Security*, *Health and Sanitation*, *Education*, *Psycho-social Activities*, *Aid Distribution* and *Transportation*. Detailed refugee camp administrative issues chart can be seen in Figure 2.7.

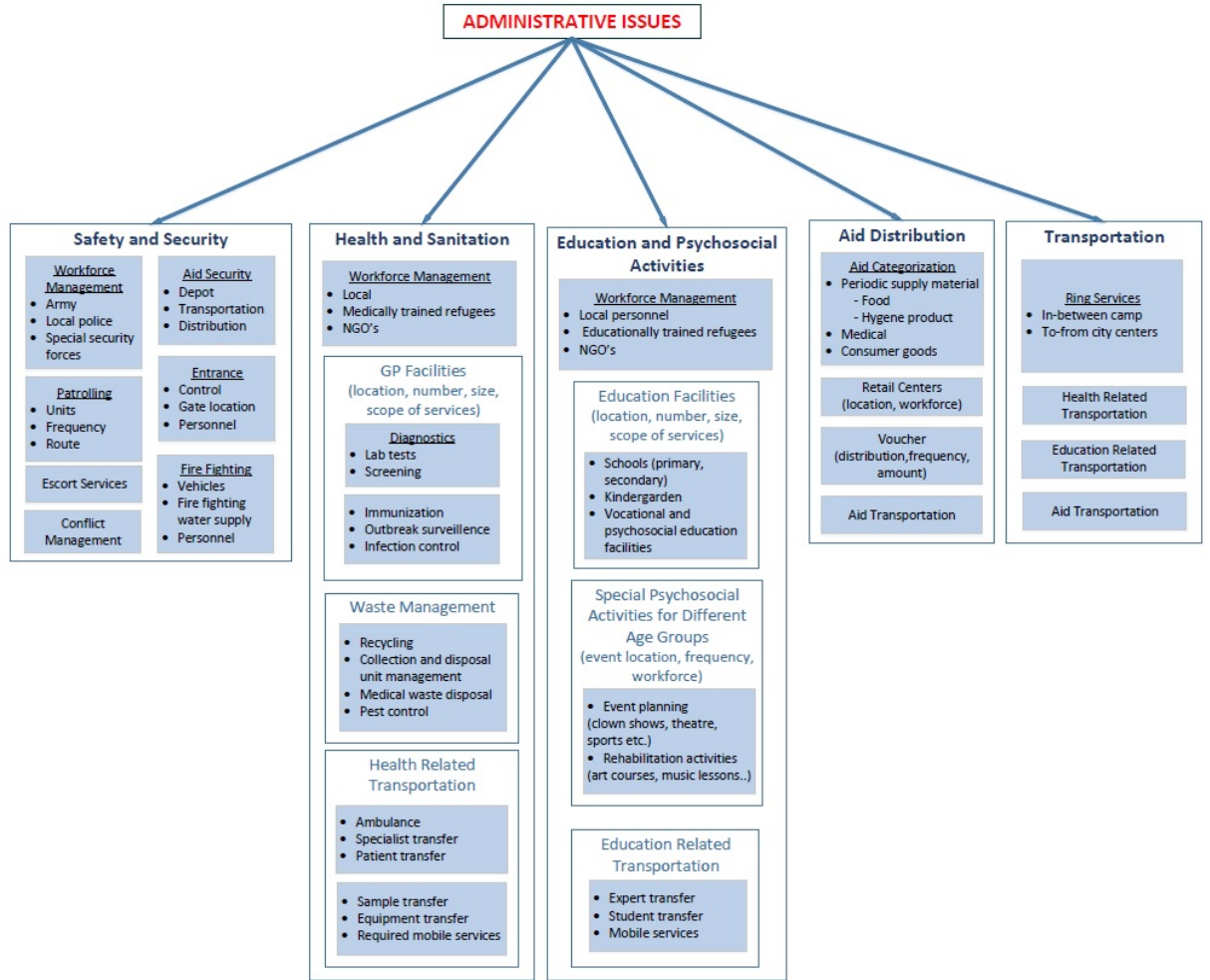


Figure 2.7: Refugee Camp Administrative Issues

As a side mission, records should be kept for various operations in the camp, thus a database system should be formed that records activities such as information on the entrance and exit of the camp, healthcare services provided to each individual, information of birth and death, aid distribution to each family [36].

2.5.1 Safety and Security

Ensuring safety and security of the residents in a camp is one of the most crucial duties of camp administration. Like other sections, while designing the security systems of the refugee camps, minimal standards and requirements in the provided references [37] should be considered. The managers should consider both conflict within residents and/or personnel and potential threats from outside of the camp. Thus, gates and checkpoints should be secured and patrolling units should be employed. Depending on the technological availabilities, surveillance systems can also be utilized.

In addition to the violence prevention, security of the in-kind donations is also of utmost concern. Thus, the storage areas should also be secured and escort services during the transportation of donations should be planned. To take an example, in the Somalia refugee camp, security is responsible for fetching aid items safely [4]. Escort service requirement is not limited to aid transportation, but can also be used for other transportation services required for the camp residents, personnel and volunteers.

Another issue that can endanger camp safety is outbreak of fire. The risk of fire is even more pronounced since the living areas are mainly tents which are more vulnerable to fire, residents may use fire-pits for cooking and heating and potential of spreading is high. Thus camp management should take necessary measures and employ enough personnel and equipment to respond such emergencies.

The prominent OR problems related to safety and security are mainly workforce selection among the alternatives and assignment. Possible alternatives for security personnel include army, gendarme, local police or special security forces. Once the crew is determined, the frequency of visits and the tours whenever applicable should also be clarified, which also brings routing and scheduling problems.

2.5.2 Health and Sanitation

Refugee health is one of the most important aspects to consider in camp management. Thus, health care of refugees is studied in the literature from different viewpoints. In the reference book provided by Doctors without Borders (Mèdecins Sans Frontières) [31], health issues are discussed in three sub categories as the emergency, the post-emergency, and repatriation and resettlement phases. The role of public health in overall disaster management is explained by Noji [38], which includes discussion on refugee health from the epidemics, immunization and nutrition perspectives. There are also studies that evaluate health care services at refugee camps (See Sahlool et al. [39] for an example at Syrian refugee camps in Turkey). A number of good practise guidelines are also available for healthcare service planners to be initiated and act as a guide for health assessment, planning, monitoring and surveillance by listing minimum standards and essential healthcare programs ([40],[6],[7]).

According to the scope of health care to be provided in the camps, which has been decided during the establishment phase, different health services can be offered to refugees. For instance, if preventive healthcare services are provided, vaccinations can be done in order to prevent epidemics. To take another example, if diagnostics services are provided, lab tests and screenings for different diseases can be conducted, which may require medical transportation to the dedicated hospitals. On the other hand, some health care services should be provided in any case, independent from the scope of services. Since an epidemic disease is likely to be seen in crowded areas such as refugee camps, outbreak surveillance activities should be conducted. In addition, camp health managers should be aware of the infection risks, and conduct infection control. Specialists such as psychologists and psychiatrists should also support refugees.

The scope of health services determines the capacity of health care facilities and the range of expertise of the doctors. If a healthcare facility is not set up in the camp or if in-house health care facilities are inadequate, or can only provide the basic service in a limited scope, mobile or external support may be used

as back up solutions to provide health services at the required level. Mobile mammography screening can be an example for required mobile services.

There are also a number of health related transportation arrangement requirements in the camp. If comprehensive healthcare cannot be provided to refugees, ambulances or helicopters should be provided in the camps for patient transfer to the hospitals in emergency situations. The organization of the shuttles that will carry specialists to the camps needs to be planned considering the frequency of visit. Likewise, if medical analysis services will be provided to refugees, samples should periodically be carried to the labs for testing. Periodical equipment transfer may also be needed. Moreover, if an on site pharmacy is not available, medicine should be transported to the camp.

Additionally, in crowded communities like refugee camps, risk of epidemics is high. Hence, preventive care such as periodical vaccinations should be provided (for an example vaccination planning model, see Jacobson et al. [41]). Besides, monitoring the quality of health care services is also an important issue. Data on certain clinical indicators can be kept to assure that the services are of good quality.

To ensure adequate sanitation, collection and disposal of daily garbage should also be taken into consideration. Trash cans must be placed in specific points in the camps and cleaning workers and waste collection vehicles should provide cleaning services regularly. In order to prevent epidemics, proper sanitation processes such as recycling, bone grinding, medical waste disposal, pest control and debris collection should be implemented.

Health administration leads to several OR problems such as workforce allocation and scheduling (of doctors or nurses) and any related transportation problems, like periodic routing problem for scheduling the visits of specialists. The periodic tests and preventive care vaccinations also lead to scheduling and routing problems. An emergency situation creates a logistics problem of how to move the patient to the hospital. Capacity planning that ensures an adequate service level is also among the OR problems that need to be tackled in this heading.

2.5.3 Education and Psycho-social Activities

Due to the fact that refugee camps can serve long periods of time, camp management should consider running educational facilities serving all age groups, if possible. Language barrier is one of the main reasons for having education facilities within the camps. Depending on the regulations of the host country, native teachers from the residents could be utilized in these schools, which would also help in providing occupation and preventing language barrier issues. If in-house education option is not sufficient, then local facilities in the surrounding area of the hosting municipality may be utilized. This option brings additional concerns regarding transportation and security of the students.

In addition to basic educational services, camp management should also plan certain activities for potential occupational purposes such as carpentering, sewing, computer usage etc. These types of courses would help residents to gain new skills which could be utilized as occupation in daily camp life, as well as providing psycho-social support for rehabilitation.

Considering every day life of camp residents, planning social events such as clown shows, theatre, movie nights, sports events and concerts is important. Depending on the availability of the residents and or volunteers, certain art courses (painting, marbling, drama) can also be planned, which, again is helpful for psychological recovery. These activities are utmost concern for kids considering their vulnerability. Professional help from social workers, psychologists, sociologists and pedagogues should be provided for the rehabilitation of kids in the camps [42].

In Turkey, Ministry of Family and Social Policies has been working on psycho-social rehabilitation by means of its psychologists, sociologists and pedagogues. Senior instructors perform activities in kindergartens to contribute to the personal developments of kids and to provide psycho-social support. For instance, in the central tent city in Adiyaman, there are playgrounds and sports fields

The OR problems involved in the education activities are analogous to their counterparts encountered in the urban education system. Workforce planning (local personnel of country of asylum, educationally trained refugees or staff of NGO's), scheduling, assignment are the main topics to be considered. For the outsourced events, event choice and location selection, resource planning and frequency determination are the main decisions that can utilize OR tools.

2.5.4 Aid Management

Aid management is certainly one of the crucial aspects in camp management. The challenge of aid management is mainly due to both supply and demand uncertainty in terms of type, amount and time of the aid items. The demand will be shaped based on the requirements of the camp residents and can include a wide range of items not restricted to nutritional requirements and daily clothing but also diapers, baby food and also health and hygiene products.

On the other hand, especially in the beginning, supply is highly uncertain and it is not derived by the demand. There are many examples (see the book by Tomasini and Van Wassenhove [43]) of unneeded material blocking the supply chain of the necessary items such as bicycles in Japan tsunami or bikinis and swimsuits in Haiti earthquake.

Thus, the first issue to be handled in aid management appears to be demand determination in order to drive the supply as much as possible. This will not only help in balancing the demand and supply, but will also contribute towards an efficiently running supply chain.

Customarily, NGOs are very active in calling for required materials in camps. Each one runs different campaigns based on the qualifications of their specific NGO. Usually, information flow between NGOs is not very well-established and thus camp management should coordinate the aid coming from these units in order to use these key resources efficiently and effectively [44].

Once the aid starts to flow through the camp, the issue of storing, securing and distribution becomes apparent. Especially during storage, the perishable nature of the aid material should also be taken into account, and thus camp management should also consider warehouse management issues including the layout decisions, allocation of the material within the layout and warehouse operating policies such as first in first out.

Obviously, an effective warehouse management would require a database system that includes all related and necessary information including the type, amount, and shelf life of the aid. The database should register both entry of the aid and its delivery to its destination. The destination can either be a family in a tent or common use facilities such as healthcare facilities, education facilities and main kitchen. Depending on the geographical dispersion and the location of the depot in the camp, camp management may decide to operate additional small-sized distribution units. These distribution units will customarily be located in the plazas so that residents can reach them easily, and will distribute frequently used items such as diapers, shampoo and dry food for the tents running their own kitchens. Security, storage and data management are also relevant for these distribution units. The synchronisation of the databases of the distribution units with the main warehouse(s) is crucial.

Distribution of the required aid material to common use facilities will usually be from the main warehouses and the required transportation will be discussed in Section 2.5.5. All related security issues are discussed in Section 2.5.1.

As evident, there are many OR problems faced during aid management. These include the problems such as location (in determining the location of the warehouse and distribution units), workforce planning and allocation (while coordinating NGOs) and routing for the distribution of aid to common use facilities.

In addition to previously discussed problems, aid management results in additional OR problems such as layout and material handling as well as inventory management. Combination of these decisions are of course part of the overall supply chain of the camp and there are studies in the literature which focus on

certain parts of these supply chain management problems ([45],..., [46]).

Recently, there have been different applications of voucher systems, which are very good means for diverting in-kind donations towards cash. As an example, TRC distributes cash cards to the Syrian refugees in Turkey [18] in the scope of E-VOUCHER Program (WFP/TRC Food Card). To take another example, in a Syrian refugee camp in Jordan, UNHCR [47] provides cash assistance to refugees in the camps through Cash on Wheels project, in which a car carries an ATM machine through the camp. In the literature, Besiou and Van Wassenhove [48] discuss food or cash distribution in the scope of socially responsible operations. The design of such voucher systems will define new OR problems to the literature which involve decisions related to frequency and amount determination, distribution and monitoring.

2.5.5 Transportation Services

In the previous sections for each heading, several issues related to transportation have been discussed. Section 2.5.2 details transportation needs for health and sanitation activities which include transferring patients to main hospitals outside the camp, shuttle services for periodic visits of specialists, collection and distribution services of specimen, blood and medicine. Similar transportation activities will also be required for educational and psychosocial purposes. These may include shuttle services for teachers, transfer of pupils, and if necessary, psychologists. Thus, camp management should ensure that these periodical trips could be carried out.

Refugees may desire to go outside of the camp for different reasons such as visiting their relatives living in other refugee camps. For such purposes, periodical ring services can be provided between different camps.

Transportation services will also be required between the warehouse(s), the distribution centers and common service areas like healthcare and educational facilities. Planning the frequencies of these transportation activities is also crucial.

In its essence, transportation is one of the basic OR problems. Thus, there are many variants that can be defined which would be relevant in transportation services of camp management. Classical location-allocation problems, routing problems and periodic routing problems are among the OR problems that will definitely be seen in camp operations. One may even define new variants of those classical OR problems by considering the detailed operational dynamics of refugee camps.

2.6 Conclusion

In this section, our main motivation is to provide an overall framework for the general refugee camp management problem and to link the OR literature with different phases of camp management.

Refugee camp management is a problem that can arise in a diversity of regions, each with different settings and requirements. Thus, the proposed framework aims to cover all possible circumstances in various camps. We differentiate the decisions based on their levels as strategic (constituting the establishment phase) and tactical and operational, which are discussed in the administration phase. We also highlight main challenges and dynamics of the decision making problems encountered in different phases of the proposed framework, which may constitute many different problems in the OR literature, and each of which can open new venues for future research.

In the remainder of the thesis, clean water infrastructure design problem, one of the sub-problems of establishment phase (explained in Section 2.3.1), is discussed. This newly proposed problem is analyzed utilizing OR tools. The problem definition, assumptions and literature review are presented in Chapter 3, and the model development, solution methodologies and computational analysis are proposed in the following chapters.

Chapter 3

The Water Distribution Network Design Problem in Refugee Camps and the Related Literature

3.1 Problem Definition

As stated in the previous chapter, there are various elements to be considered in the establishment and administrative phases of a refugee camp. In the establishment phase, there are three major infrastructure decisions (see Figure 2.4), provision of clean water to refugees adequately and effectively is one of them. In the remainder of the thesis, we approach the clean water network design problem in refugee camps, explained in Section 2.3.1.

While designing a water distribution network in a camp, we take into consideration various elements of the network such as wells, water distribution units (WDUs), pipelines and multiple objectives. Here, WDU is a generalization and it represents all types of water distribution points such as water taps, kitchens,

bathrooms or restrooms. Figure 3.1 shows an example for a WDU.



Figure 3.1: An example to a WDU in Somalia refugee camp of TRC [4]

The proposed problem involves determining the locations of a well and WDUs, and the distribution pipes to transfer water from the well to WDUs.

In this study, we address the situation, in which, a water well is used as a water source (see Figure 3.2). Observe that, a well is the only source if public water network is not accessible from a refugee camp, there is no spring water at reachable distance, or camp area is on a dry zone. Note also that wells can only be drilled at a point where underground water exists and drilling is possible.



Figure 3.2: Somali refugee women gather around a water well. Source: UNHCR

Water network design in refugee camps is quite different from public water network design. In a public water network, water should be accessible from each demand point. Contrarily, in refugee camps, water may not be available at each tent, i.e. there is not necessarily a water tap in every tent. In this case, water is supplied to common use areas such as kitchens, restrooms and WDUs.

While locating WDUs along the camp, one should make sure that the residents of each tent will have ‘access’ to a WDU. Here ‘access’ means ensuring the distance between a tent and its closest WDU is below a certain threshold. There are various sources in the literature, that define thresholds for access to clean water; Handbook for Emergencies and The Sphere Project are the most popular of them. The list of access values in the literature is given in Table 3.1.

Table 3.1: List of sources in the literature for maximum threshold for access

Source	Required Threshold Distance
Handbook for Emergencies, by UNHCR [6]	100 meters
The Sphere Project [7]	500 meters

In this thesis, we consider the water distribution network design problem in refugee camps. Specifically, in this problem, the number and locations of a single well and WDUs and design the network between these nodes are determined by taking relevant constraints (threshold for access) into account.

The problem aims to optimize two criteria: cost and walking distance. The first objective is cost efficiency regarding, in particular, total pipe length. The second one aims more fairness and efficiency in accessibility of WDUs, which is calculated as the total walking distance of refugees. In addition, efficiency in walking distance is also considered by imposing accessibility constraints as thresholds.

3.2 Literature Review of the Water Distribution Network Design Problem in Refugee Camps

Water distribution network design problem in refugee camps is basically a water network design problem which involves facility location and network design decisions in the area of humanitarian logistics. Therefore, this section consists of literature reviews of two sub sections, namely refugee crisis in scope of humanitarian logistics and water distribution network design problem.

3.2.1 Literature Review of Refugee Crisis in Scope of Humanitarian Logistics

In the literature, several definitions of a disaster have been posited by various aid organizations and academicians. For instance, Van Wassenhove [5] defines disaster as ‘a disruption that physically affects a system as a whole and threatens its priorities and goals’. Additionally, Van Wassenhove [5] classifies disaster types on the basis of their causes (natural vs man-made) and emergence time (sudden-onset or slow onset) which can be seen on Figure 3.3.

		Cause	
		Natural	Man-made
Duration of Emergency	Sudden-onset	Earthquake Hurricane Tornadoes	Terrorist Attack Coup d'Etat Chemical leak
	Slow-onset	Famine Drought Poverty	Political Crisis Refugee Crisis

Figure 3.3: Disaster categorization schema [5]

The significance of disaster categorisation is that disasters in each category show differences regarding to their occurrence processes and structural features. Hence, dissimilarities should be considered and suitable precautions should be taken while managing various disasters. Therefore, while handling refugee crises and processes related to refugee camps, awareness of requisites and fulfilment of the requirements in an efficient and effective way is substantial [49].

Although the table presents a more simplified view, disasters are mostly complex, because they occur in combination of situations [50]. For instance, populations in conflict zones can experience displacement, which can lead to famine and epidemics. TRC is facing such complex disaster in Somalia [4], which is based on in that thesis, both refugee crisis and drought is coped with together. Such complex disasters are not well-studied, but they occur more frequently.

Research in humanitarian logistics is categorized according to the disaster life-cycle: (pre-disaster) mitigation, preparedness phase, (post-disaster) response and recovery phases. In pre-disaster phase, actions such as shelter site location and stock pre-positioning take place. Post-disaster phase involves such activities as evacuation to shelters, aid distribution, casualty transportation, debris removal.

In the literature, there are reviews that focus on various phases of a disaster. Altay and Green [51] are among the first to review the papers with an Operations Research and Management Science perspective. They consider all phases of emergency management: mitigation, preparedness, response, and recovery. They firstly list the OR/MS problems corresponding to each phase of emergency management, then they group the articles published until 2004 based on the phases. They conclude that real-life applications are scarce and theory development in preparedness, response and recovery is deficient.

Galindo and Batta's work [52] is a continuation of the previous review (Altay and Green [51]). They add to this work by reviewing papers from 2005 to 2010 and following up of the conclusions of Altay and Green [51]. They conclude that no significant changes in the OR/MS field have been achieved. They also state that, the studies related to man-made disasters are more popular until 2004. But

between 2005 and 2010, studies related to natural disasters are became popular.

Anaya-Arenas et al. [53] focus on relief distribution networks with logistics aspects of the problem, in scope of disaster response phase. They categorise models as location and network design, transportation (relief distribution and casualty transportation) and combination of location and transportation.

Özdamar and Ertem [54] provide a review on the post-disaster phase disaster lifecycle. They divide post disaster phase as response and recovery. In the response phase, they discuss several vehicle representation styles involving models with capacitated vehicles, relief delivery and casualty transport and evacuation. Under the title of recovery phase, they analyse models for infrastructure restoration and debris removal. In addition, they mention the usage of real-life information systems in humanitarian logistics literature.

The review articles referred above show that studies related to humanitarian logistics mainly deal with natural disasters. The analyses specific to refugee camps in the scope of humanitarian logistics are very scarce, the studies especially with the OR point of view nearly do not exist (recall the literature review in Chapter 2).

3.2.2 Literature Review of Water Distribution Network Design Problem

There are few studies related to water consumption and treatment in refugee camps, which are referred to in Section 2.3.1. In this section, the more general problem - water distribution network design problem both encountered in urban and rural areas - is reviewed.

Alperovits and Shamir [55] are the first researchers that consider the water network design problem in the literature. Alperovits and Shamir [55] and Eiger et al. [56] develop systems that determine the pipe length and radius when the design of water distribution network is given. There are studies that use heuristic methods from the literature such as simulated annealing and harmonic search for this non-linear problem ([8],[57],[58],[59]).

Farmani et al. [60] approach the problem from a multi criteria point of view. They use cost and utilization as their decision criteria and solve the same problem using two multi criteria evolutionary algorithms: non-dominated sorting genetic algorithm (NSGA) [9] and strong pareto evolutionary algorithm (SPEA) and compare the obtained results. Dutta et al. [61] and Esquivel et al. [62] observe the underground water using geographical information systems (GIS) and use multi criteria analysis methods to optimize the monitoring network system. Udias et al. [63] develop multi criteria evolutionary algorithms for water treatment and analyze the trade-off between cost and water quality. Tanyimboh et al. [64] use two different methods to design water network. They develop a multi-objective genetic algorithm and a stochastic search program which uses the concepts of evolution and a heuristic method. Maier et al. [65] use evolutionary algorithms and other meta-heuristics to attempt multi criteria optimization of water supply usage. Iancu et al. [66] analyse the trade-off between network length and cost criteria in water network design. There are also some reviews in the literature that group the studies based on their modelling and solution techniques [67].

In the studies that are mentioned, developed models and solution methodologies are used for finding the optimal pipe diameter and length, mostly for the given network of the cities such as New York and Hanoi. In such distribution systems, layout is pre-established. The main difference between the studies conducted in the literature and our work is the fact that network design of cities are predetermined (i.e., the locations of both supply and demand nodes and the placement of pipes are known) and the only concern is deciding on the specifications (radius and length) of the pipes, while in our problem we do not have such a predetermined network, actually we aim to determine the network design. Additionally, these studies do not focus on any shelter site or refugee camp water distribution network design. However, in our study, we aim to develop models that design of water network of a refugee camp.

In the literature, the study of Nolz et al. [68] is the one that has the most resemblance to our work. The first similarity is that, we both handle the problem optimizing two objectives. Both of us consider cost as one of the objectives: Nolz et al. [68] calculate cost as a function of total tour length, and we define cost as total network length. The other similarity is that, we both use NSGA-II algorithm to solve our problems.

Nolz et al. [68] design a location-routing model for planning water distribution tours in disaster relief. They aim to develop a decision support system (DSS) which can be used both pre and post disaster phases. The algorithm in this DSS works with data, that is available before a disaster. When a disaster occurs, information can be updated such as damaged roads or available vehicle.

Nolz et al. [68] consider a realistic setting with heterogeneous modes of transportation and different road categories. To better explain the water distribution tours, one drinking water treatment plant is embedded in a depot. The depot is also a starting point and vehicles make tour in order to distribute clean water to the population center nodes. A population center node is covered if the people living there are able to reach a water distribution point within 2 hours travel time.

The described problem aims to find optimal route, travel modes and population nodes to be visited while optimizing two objectives. The first objective is a combination of the minisum facility location criterion and weighted maximal covering location criterion. The second objective is a cost criterion, measured in terms of tour length. Considering the problem requirements and multiple objectives stated before, a DSS is developed, using a multi-objective meta-heuristic algorithm (NSGA-II).

However, there are some crucial discrepancies. First of all, in our models, we have to cover all nodes within a certain threshold, which is guaranteed by covering constraint. But in Nolz et al. [68], population center nodes are not necessarily covered completely and one of their objectives is minimizing the number of population uncovered. The second difference is, Nolz et al. [68] make water distribution tours, i.e. routings. Contrarily, we do not design water distribution routing, we design the water distribution network.

To the best of our knowledge, there are no studies that find the optimal clean water network design for a refugee camp while determining the locations of water source and WDUs. Our study considers minimal requirements and different objective functions, and thus offers an important contribution to the literature.

Chapter 4

Model Development

The water network design problem that is addressed in this chapter aims to locate WDUs, a water well and to determine the distribution network between these components. In order to address the problem, mixed integer linear programming models are formulated. Given:

- The locations of settlements, WCs, kitchens . . .
- Threshold distance for access of refugees
- Maximum number of WDUs
- Alternative well locations based on the underground water network

The models aim to find:

- The location of well
- The locations of WDUs
- The design of water network

Different objective functions can be utilized in these models. The first objective that can be considered is minimizing the construction cost of the network. However, this is a humanitarian problem, therefore decision makers should also

consider water accessibility to refugees. Thus and so, in this problem, two objectives are defined: the first objective is construction cost, which is a function of the total pipe length. The second one is the total distance from each residential point to its closest WDU. With this objective we aim to provide reasonably easy access to water.

Preliminarily, single-objective models are formulated for both objectives, separately. We first assume that, there is one well whose location is fixed and known. Then, we model the case in which the well location is to be selected among the candidate well locations, which are determined based on the underground water information. The single objective models are developed to provide transition to the bi-objective models.

As stated before, in the proposed problem, basically, the locations of well and WDUs are decided and the network between them is designed. Thus, in that aspect, the problem resembles facility location and network design problems [69], especially covering problems.

As discussed in Section 3.1, in a refugee camp, water may not be available and accessible at each tent, so WDUs are located within the camp to provide water. However, any proposed model to this problem has to consider the maximum walking distance between a tent and its closest WDU and should cover all tents within the maximum distance, refugee camp water network design, making the model formulation similar to that of the set covering problem [70]. Specifically, the covering constraint of the set covering problem, which ensures that the distance between a customer and its closest facility is lower than a certain threshold (defined as γ in Section 3.1), is also valid and to be used in our problems.

Although both of the problems resemble each other in terms of considering the maximum threshold distance between residents and facilities, the set covering problem cannot ensure the entire characteristics of the proposed problem. There are some different points to take into account in the refugee camp clean water network design.

First of all, in the set covering problem, locations of facilities are determined but the network flow in between is not decided. However, in the water network design, network flow between wells and WDUs is required to be planned. Thus, flow balance constraints of the water network should be stated in the models.

Another difference between the two problems is the objective functions. In the set covering problem [71], the objective is minimizing the total number of located facilities. In our case, the maximum number of facilities can be located (p) is bounded by a constraint. In our problem, minimizing total network length (i.e. cost) and minimizing total walking distance of refugees to the nearest WDU are possible objectives for a refugee camp water network design problem.

We categorize the single objective models according to their objectives: minimizing total network length and minimizing total walking distance. We further categorize the models based on the well location (fixed versus unfixed) both fixed and unfixed well location models, there will be only one well to be drilled. In the fixed well location models, we assume that the location of well is predetermined and it is given to the model as a parameter. In the unfixed well location, models decide the location of well among the candidate well locations. Table 4.1 below shows our categorization as well as the names we give to each of these models.

Table 4.1: Table of abbreviations for mathematical models

	Network Length	Walking Distance	Bi - Objective
Well is fixed	WF-L	WF-D	Bi-WF
Well is not fixed	WNF-L	WNF-D	Bi-WNF

In the table, WF implies that the location of well is fixed and WNF means that well location is not fixed, in other words, models will decide the location. Suffix -L stands for minimizing total network length while -D stands for minimizing total walking distance of refugees. Finally, prefix Bi denotes Bi-objective optimization models. These abbreviations will be used in the remainder of the text.

In order to formulate the above problems, we define the sets, parameters and decision variables given in the following nomenclature.

Nomenclature for common sets and variables

Sets

$\mathcal{I} = \{0, 1, 2, \dots, n\}$: The set of water demand points, and set of locations that a WDU can be established in

Parameters

d_{ij} : The distance between point $i \in \mathcal{I}$ and $j \in \mathcal{I}$

p : maximum number of WDUs

γ : maximum distance allowed between a demand point and its closest WDU

$$a_{ij} = \begin{cases} 1, & \text{If } d_{ij} \leq \gamma \\ 0, & \text{Otherwise} \end{cases}$$

M : a very large number

Decision Variables

$$y_i = \begin{cases} 1, & \text{If a WDU is installed at } i, i \in \mathcal{I} \\ 0, & \text{Otherwise} \end{cases}$$

$$z_{ij} = \begin{cases} 1, & \text{If a pipe is installed between points } i \text{ and } j; i, j \in \mathcal{I} \text{ (if } x_{ij} > 0) \\ 0, & \text{Otherwise} \end{cases}$$

x_{ij} = total number of WDUs after point i (including j) connecting by a pipe

Here, WDUs are located at the demand points in the camp, thus, the set of demand points $\mathcal{I}$ also represents the set of locations that each WDU can be established.

Decision variable y_i shows whether a WDU is located at point i or not. z_{ij} is used for network design. If WDUs are installed at points i and j and there is a pipe installed between these points, z_{ij} equals to 1. Variable x_{ij} is defined for connectivity between points i and j . This variable depends on whether the pipe between the points is installed (z_{ij}). x_{ij} variable also represents the total flow between points i and j .

In the mathematical models given in 4.1, there is single well and multiple WDUs and the network topology between well and WDUs is routed tree.

We now discuss our models in detail.

4.1 For Fixed Well Location (WF-L and WF-D)

In this section, we model the problem under the assumption that the location of the well is predetermined and given to the model as a parameter. Thus we define set s , which is a subset of set $\mathcal{I}$. Well set s includes only one element and it shows the index of the fixed well location to be drilled.

s : The location of water well (predetermined) $s \in \mathcal{I}$;

We develop models for both objectives: minimizing total network length (WF-L) and minimizing total walking distance (WF-D), respectively. The models of WF-L and WF-D are presented in the following sub-sections.

4.1.1 Minimize total network length (WF-L)

Considering the requirements of the problem and its structural characteristics, utilizing nomenclature and set s defined above, we model the problem for fixed well and minimizing total network length.

$$\begin{aligned}
(WF-L) \quad & \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot z_{ij} \\
& \text{Subject to} \\
& \sum_{i \in \mathcal{I}} a_{ij} \cdot y_i \geq 1 \quad \forall j \in \mathcal{I}, i \neq j \quad (4.1) \\
& \sum_{i \in \mathcal{I}} y_i \leq p \quad (4.2) \\
& \sum_{i \in \mathcal{I} - \{s\}} x_{si} = \sum_{i \in \mathcal{I} - \{s\}} y_i \quad \forall s \in S \quad (4.3) \\
& \sum_{i \in \mathcal{I}} x_{ik} - \sum_{i \in \mathcal{I}} x_{ki} \geq y_k \quad \forall k \in \mathcal{I} - \{s\}, k \neq i \quad (4.4) \\
& 0 \leq x_{ij} \leq M \cdot y_j \quad \forall i, j \in \mathcal{I} \quad (4.5) \\
& 0 \leq x_{ij} \leq M \cdot z_{ij} \quad \forall i, j \in \mathcal{I} \quad (4.6) \\
& y_i, z_{ij} \in \{0; 1\} \quad \forall i, j \in \mathcal{I} \quad (4.7) \\
& x_{ij} \text{ integer} \quad \forall i, j \in \mathcal{I} \quad (4.8)
\end{aligned}$$

In this formulation, the objective function is minimizing total network length, which is calculated as total pipe length.

Constraint (4.1) is mandatory closeness constraint of set covering problem [70]. It ensures that the distance between each residential point and its closest WDU is less than or equal to accessibility threshold (γ). Constraint (4.2) guarantees that the total number of WDUs is less than or equal to p .

Constraints (4.3) and (4.4) stand for flow balance of the water network. Constraint (4.3) implies that, the total outflow from the point of water well (point s) should be equal to the total number of WDUs established, excluding point s . In Constraint (4.4), it is specified whether a WDU is installed at point k (in which case y_i is 1), the difference of the incoming and outgoing flow of point k should be greater than or equal to 1.

Constraints (4.5) and (4.6) ensure connectivity of decision variables. Constraint (4.5) implies that, if there is no WDU established at point i (i.e. y_i is 0), then there can not be any flow from i to j (i.e. x_{ij} should be 0). Similarly, if there is no pipe installed between i and j (i.e. z_{ij} is 0) then there can not be any flow from i to j (Constraint 4.6). For the maximum value that M can take, p is sufficiently large for the models.

Constraint set (4.7) is the set of binary constraints on the decision variables y_i and z_{ij} . Constraint (4.8) stipulates that decision variable x_{ij} can take only integer values.

4.1.2 Minimize total walking distance (WF-D)

In this section, the sets and parameters given in the nomenclature, decision variables are also the same, but one additional decision variable should be defined to keep track of the individual walking distance of each refugee. The additional decision variable is as follows:

$$u_{ij} = \begin{cases} 1, & \text{If WDU at point } i \text{ covers demand point } j; i, j \in \mathcal{I} \\ 0, & \text{Otherwise} \end{cases}$$

Utilizing the sets, parameters and decision variables, and considering the problem requirements, we formulate the following model:

$$\text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij}$$

Subject to

$$(4.1) \dots (4.8)$$

$$\sum_{i \in \mathcal{I}} u_{ij} \geq 1 \quad \forall j \in \mathcal{I}, i \neq j \quad (4.9)$$

$$u_{ij} \leq y_i \quad \forall i, j \in \mathcal{I} \quad (4.10)$$

$$u_{ij} \in \{0; 1\} \quad \forall i, j \in \mathcal{I} \quad (4.11)$$

In model WF-D, the objective function is minimizing total walking distance of refugees. However, when the model is solved using this objective function, it has been observed that the water distribution network is not installed properly. To make it clear, water network is designed as a star network. In other words, for each individual WDU, there is a different pipe installed from the well. Star network is not desired in our case. In order to eliminate this problem, the objective function given in 4.1.1 (total network length) is lexicographically added to the objective. Updated objective function is given below:

$$(WF - D) \quad \text{Minimize} \quad \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij} + \lambda \cdot \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot z_{ij}$$

The new objective includes two parts: in the first part, total walking distance of refugees is calculated. In the second part, the total network length is computed. Note that we multiply the second part with a small parameter lambda (λ). This is to ensure that, among the solutions with minimum total walking distance, we find the one that gives the minimum network length.

Constraints (4.1)...(4.8) of the previous formulation also apply to this formulation. However, there are additional constraints in this model. Constraint (4.9) represents the coverage of each demand point j with its closest WDU. Constraint (4.10) stands for connectivity of decision variables y_i and u_{ij} . Constraint (4.11) is a binary constraint on the new decision variable u_{ij} .

4.2 Well location is to be determined (WNF-L and WNF-D)

In this section, the location of well is not fixed and it will be selected among candidate well locations based on the underground water network information. Thus, we define a new set S_2 to indicate the candidate well locations. Set s in the previous formulations is not used in this section.

S_2 = Set of candidate water well locations, $S_2 \subset \mathcal{I}$;

Here, set of candidate well locations is a subset of all demand points in the camp ($\mathcal{I}$). Additionally, a new decision variable is defined to choose the location of water well to be drilled. This location is chosen among the elements of set S_2 .

$$w_s = \begin{cases} 1, & \text{If water well is drilled at point } s; s \in S_2 \\ 0, & \text{Otherwise} \end{cases}$$

4.2.1 Minimize total network length (WNF-L)

In this subsection, WF-L model is modified utilizing the new decision variable and the set defined above. Decision variables, sets and parameters are also the same as in the nomenclature.

$$\begin{aligned}
(WNF - L) \quad & \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot z_{ij} \\
& \text{Subject to} \\
& (4.1), (4.2), (4.6), (4.7), (4.8) \\
& \sum_{i \in \mathcal{I}} x_{ik} - \sum_{i \in \mathcal{I}} x_{ki} \geq y_k - M \cdot w_k \quad \forall k \in \mathcal{I}, k \neq i \quad (4.12) \\
& \sum_{i \in S_2} w_s = 1 \quad (4.13) \\
& \sum_{i \in \mathcal{I}/S_2} w_s = 0 \quad (4.14) \\
& 0 \leq x_{ij} \leq M \cdot (y_j + w_j) \quad \forall i, j \in \mathcal{I} \quad (4.15) \\
& w_s \in \{0; 1\} \quad \forall s \in S_2 \quad (4.16)
\end{aligned}$$

The new decision variable w_s is used for determining the location of water well. It is assumed that all candidate water wells have the same characteristics (with respect to water capacity etc.) The set of candidate well locations is designated by groundwater information.

The objective function minimizes the total network length as in the WF-L model. Constraints (4.1), (4.2), (4.6), (4.7) and (4.8) are also used in this formulation. Five new constraints are added to the WF-L model. Flow balance Constraints (4.3) and (4.4) of WF-L model are turned into (4.12), (4.13) and (4.14) which guarantee the flow balance of network considering the well for this formulation.

Constraint (4.12) is the same with Constraint (4.4) except $-M \cdot w_k$ part. $-M \cdot w_k$ makes the constraint non-binding if there is a well located at point k (if w_k is 1). Because Constraint (4.12) indicates the difference of the incoming and outgoing flow of point k should be greater than or equal to 1, if a WDU is installed at point k (i.e. $y_k=1$). However, when there is a well at k , there will be no inflow, thus this constraint should be non-binding.

Constraints (4.13) ensures that a water well can only be drilled in one of the candidate well locations (S_2). Likewise, Constraint (4.14) guarantees that a water well can not be located at a point if it is not a candidate location ($\mathcal{I}/S_2$).

Constraint (4.15) is required for connectivity of the decision variables y_j , w_j and x_{ij} . This constraint implies, if there is pipe between point i and j , (i.e. $x_{ij}=1$), there should be either well or WDU (or both of them) located at point j .

4.2.2 Minimize total walking distance (WNF-D)

In this section, location of water well to be drilled is not predetermined and objective is minimizing total walking distance of refugees. Therefore, sets and parameters are the same with model WF-D. Thus, the model of this section takes the following form:

$$\text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij}$$

Subject to

$$(4.1), (4.2), (4.6) \dots (4.16)$$

Same reason with WF-D, total network length is lexicographically added to the main objective (total walking distance). Updated objective function is given below:

$$(WNF - D) \quad \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij} + \lambda \cdot \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot z_{ij}$$

4.3 Bi-Objective Formulations of the Problem (Bi-WF and Bi-WNF)

The models of WF-L and WNF-L have the objective of minimizing total network length i.e. the construction cost of the network. When these models are solved using CPLEX, in most of the solutions, it is observed that WDUs are located very close to each other and clustered at a certain area while most of the residential points in the camp are far from the WDUs in order to make network length as short as possible. This means that; some refugees are pretty close to WDUs, they even have more than one WDU in a very short distance. On the other hand, majority of the refugees have their closest WDU at a distance of γ (accessibility threshold). This situation leads to inefficiency in the usage of WDUs and walking distance of refugees.

In order to provide more efficient water access to refugees, the objective function of models WF-L and WNF-L have been changed and total walking distance of refugees is considered as a new objective. The altered models are presented in WF-D and WNF-D.

Incorporating these two objective functions, the problem can be formulated bi-objectively and solved by using multi criteria decision making methods. Solving bi-objective models helps the decision maker to see the entire set of pareto optimal solutions and the trade-off between two objectives. The proposed bi-objective models for the cases where the location of well is fixed (Bi-WF) and where location of well is to be decided (Bi-WNF) are presented in the following sub-sections.

4.3.1 Bi-Objective model fixed well location (Bi-WF)

In order to model bi-objective form of the problem, two objectives are defined: minimizing total walking distance and minimizing total network length. The sets, parameters and decision variables are identical with the WF-D model. The problem requirements are also the same, thus the constraints of WF-D are used as they are. The modified model is as follows:

$$\text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij}$$

$$\text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot z_{ij}$$

Subject to

$$(4.1) \dots (4.11)$$

4.3.2 Bi-Objective model for well is to be fixed (Bi-WNF)

In order to obtain Bi-WNF, we modify the WNF-D model is as follows:

$$\text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij}$$

$$\text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot z_{ij}$$

Subject to

$$(4.1), (4.2), (4.6) \dots (4.16)$$

4.4 Extension of the Models

In the previous models, we made some basic assumptions in order to simplify the problem. In this section, we relax some of the assumptions and modify the bi-objective models.

4.4.1 Including Capacities

Previously, we assume that the capacities of the pipes are identical. But in the real life, there can be different types of pipes with different capacities. As arc capacities change, construction costs will also change. In order to formulate the corresponding model, we need additional decision variables and parameter.

c_k = The unit cost of installing pipe type k , $k = 1, 2$;

f = The threshold flow (above type 1 and below type 2 pipes will be used);

Instead of z_{ij} variable, we define z_{ij}^k :

$$z_{ij}^k = \begin{cases} 1, & \text{If a pipe type } k \text{ is installed between points } i \text{ and } j; i, j \in \mathcal{I} \text{ (if } x_{ij} > 0), k=1,2 \\ 0, & \text{Otherwise} \end{cases}$$

$$t_{i,j} = \begin{cases} 1, & \text{If } x_{ij} > f; i, j \in \mathcal{I} \\ 0, & \text{Otherwise} \end{cases}$$

We assume that, there are two types of pipes and if flow amount is more than f (if $x_{ij} > f$), pipe type 1 is used; otherwise type 2 pipe is utilized.

Using the new parameters and decision variables, the bi-objective models are modified. Modified Bi-WF model is given as follows:

$$\begin{aligned}
& \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij} \\
& \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} c_1 \cdot d_{ij} \cdot z_{ij}^1 + c_2 \cdot d_{ij} \cdot z_{ij}^2 \\
& \text{Subject to} \\
& (4.1) \dots (4.11) \\
& z_{ij}^1 + z_{ij}^2 \leq 1 \quad \forall i, j \in \mathcal{I} \quad (4.17) \\
& x_{ij} - f \leq M \cdot t_{ij} \quad \forall i, j \in \mathcal{I} \quad (4.18) \\
& 1 - z_{ij}^1 \leq M \cdot (1 - t_{ij}) \quad \forall i, j \in \mathcal{I} \quad (4.19) \\
& (f + 1) - x_{ij} \leq M \cdot (1 - t_{ij}) \quad \forall i, j \in \mathcal{I} \quad (4.20) \\
& 1 - z_{ij}^2 \leq M \cdot t_{ij} \quad \forall i, j \in \mathcal{I} \quad (4.21) \\
& 0 \leq x_{ij} \leq M \cdot (z_{ij}^1 + z_{ij}^2) \quad \forall i, j \in \mathcal{I}, k \in \{1, 2\} \quad (4.22) \\
& z_{ij}^k, t_{ij} \in \{0; 1\} \quad \forall i, j \in \mathcal{I} \quad (4.23)
\end{aligned}$$

Constraint 4.17 implies either type 1 or type 2 pipe can be implemented. Constraints 4.18 and 4.19 guarantee if flow amount between points i and j is more than f (i.e. if $x_{ij} > f$), then type 1 pipe should be used and z_{ij}^1 should be equal to 1. In other case, (if $0 < x_{ij} \leq f$), then $z_{ij}^2 = 1$ (utilizing Constraints 4.20 and 4.21). Constraint 4.6 (connectivity of x_{ij} and z_{ij}) turned into Constraint 4.22.

Utilizing the new parameters and decision variables, the model of Bi-WNF is also modified below:

$$\begin{aligned}
& \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} d_{ij} \cdot u_{ij} \\
& \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} c_1 \cdot d_{ij} \cdot z_{ij}^1 + c_2 \cdot d_{ij} \cdot z_{ij}^2 \\
& \text{Subject to} \\
& (4.1), (4.2), (4.6) \dots (4.23)
\end{aligned}$$

4.4.2 Including Populations

We also want to consider the number of people in each cluster while calculating the total walking distance of refugees. In order to do so, we define new parameters:

b_i = The total number of people live in node i , $i \in \mathcal{I}$

$$\begin{aligned} & \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} b_i \cdot d_{ij} \cdot u_{ij} \\ & \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} c_1 \cdot d_{ij} \cdot z_{ij}^1 + c_2 \cdot d_{ij} \cdot z_{ij}^2 \\ & \text{Subject to} \\ & (4.1) \dots (4.11), (4.17) \dots (4.23) \end{aligned}$$

Utilizing the parameters and decision variables, the model of Bi-WNF is also modified below:

$$\begin{aligned} & \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} b_i \cdot d_{ij} \cdot u_{ij} \\ & \text{Minimize } \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} c_1 \cdot d_{ij} \cdot z_{ij}^1 + c_2 \cdot d_{ij} \cdot z_{ij}^2 \\ & \text{Subject to} \\ & (4.1), (4.2), (4.6) \dots (4.23) \end{aligned}$$

Chapter 5

Solution Methodology

In order to solve bi-objective models, we use two types of solution methodologies, which are exact methodology and heuristic algorithms, respectively.

5.1 Exact Methodology

To find exact pareto solutions of the bi-objective models, we utilize epsilon constraint method [72]. This method is based on solving single objective models iteratively. In the epsilon-constraint method, one of the objectives is used in the objective function, while the second one is used in a constraint and bounded by an epsilon value. At each iteration, the epsilon bound on the second objective is decreased by a step size. In this way, different pareto optimal solutions are found. Such iterations are repeated in this manner, until the corresponding model becomes infeasible.

We defined the first objective (O_1) as total walking distance of refugees and the second objective (O_2) as total network length. We solve the single objective problems iteratively, each time with a different ε value, which is defined as $O_2^* - k$ below. The overall algorithm works as follows:

– **Step (1)** Solve:

Minimize $O_1 + \lambda.O_2$

Subject to

$x \in X$

Let the optimal solution vector be (O_1^*, O_2^*) .

– **Step (2)** Solve:

Minimize $O_1 + \lambda.O_2$

Subject to

$x \in X$

$O_2 \leq O_2^* - k$

If infeasible, stop. Otherwise, let the new optimal solution vector be (O_1^*, O_2^*) . Repeat Step (2).

Here, x is the decision variable vector and X is the feasible region of the corresponding problem. λ is a parameter that is used to avoid weakly non-dominated but dominated solutions. In other words, when minimizing the first objective (O_1), among the solutions that minimize O_1 the one that gives the minimum value for the second objective (O_2) should be selected. To ensure this, in the objective function, the second objective is multiplied with a small coefficient (hence the objective function becomes $O_1 + \lambda.O_2$). The coefficient λ should be small enough not to head off the first objective. In our calculations, we set λ to 0.001, which is sufficiently small because of orders of magnitude.

If the second objective function (O_2) could only take integer values, reducing the right hand side value by 1 unit (i.e. setting $k=1$) would guarantee obtaining all the Pareto solutions. However, in our problem, distance matrix does not consist of integer numbers, i.e. the second objective can take continuous values. Thus, an approximate step size k value should be defined. Approximately, k value is set at 0.1.

5.2 Heuristics

In Section 7, we solve the models for different γ values. For the objective of *minimizing total network length*, as the γ values get smaller, the problem becomes harder to solve (see Appendix B and C) for both single objective and bi-objective models. Instances of WNF-L cannot be solved in 12 hours for $\gamma=70$ or 60, thus we solve the models for 2 hours and report the solutions with gap.

The same situation is observed in bi-objective model solutions. While finding the pareto optimal solutions, the algorithm starts with the easier to solve models where the focus is *minimizing total walking distance*, so first iterations are solved in a shorter time. After a few iterations (as we approach the harder to solve *minimizing network length* side of the pareto front), the solution time of the models significantly increases.

Hence for smaller gamma values, (i.e. $\gamma=60$), for which finding Pareto optimal solutions is harder, we find approximate Pareto solutions by solving the models for 10 minutes. We take the resulting solution and report the corresponding gap, for both cases: well location is fixed and to be fixed (Bi-WF and Bi-WNF).

We use heuristic algorithms to find approximate pareto solutions. As a beginning, we developed a heuristic algorithm. In this algorithm, node clusters are created and by selecting nodes from each cluster, total walking distance and network length are calculated, and the node combinations are interchanged in each iteration. This Cluster-based Algorithm is an improvement heuristic methodology which can be considered as a variation of 2-opt algorithm.

When we run the Cluster-based Algorithm, we observe that the obtained solutions are not of good quality. For this reason, a different heuristic methodology is utilized from the literature.

The second heuristic is a modified version of a well-known algorithm from the literature. NSGA-II algorithm is adapted to the bi-objective water network design problem. We now explain this heuristic approach in detail.

5.2.1 Adapted NSGA-II

Since the improved Cluster-based heuristic does not show the desired performance, a heuristic algorithm from literature is utilized.

There are open source codes shared online for multi-objective algorithms, MOEA Framework is one of them. The MOEA Framework is a free and open source Java library for developing and experimenting with multi-objective evolutionary algorithms (MOEAs) and other general-purpose multi-objective optimization algorithms [73]. A number of algorithms are provided by MOEA Framework, including NSGA-II and III, ϵ -MOEA, SPEA2 etc.

Non-Dominated Sorting Genetic Algorithm for Multi-Objective Optimization (NSGA-II), proposed by Deb et al. [9] is utilized in this study. The MOEA Framework source code of the NSGA-II algorithm is modified taking the problem specifications into account. Objective function values (fitness function evaluation for a given solution vector): *total walking distance* and *total network length* are calculated. Prim's algorithm is used for finding the optimal total network length for a given set of candidate solution. The reason why Prim's algorithm is utilized is, this algorithm is able to find the optimal network tree [69]. After defining the problem to the MOEA Framework source code, NSGA-II algorithm is invoked. For the working principle of the algorithm, see Figure 5.1.

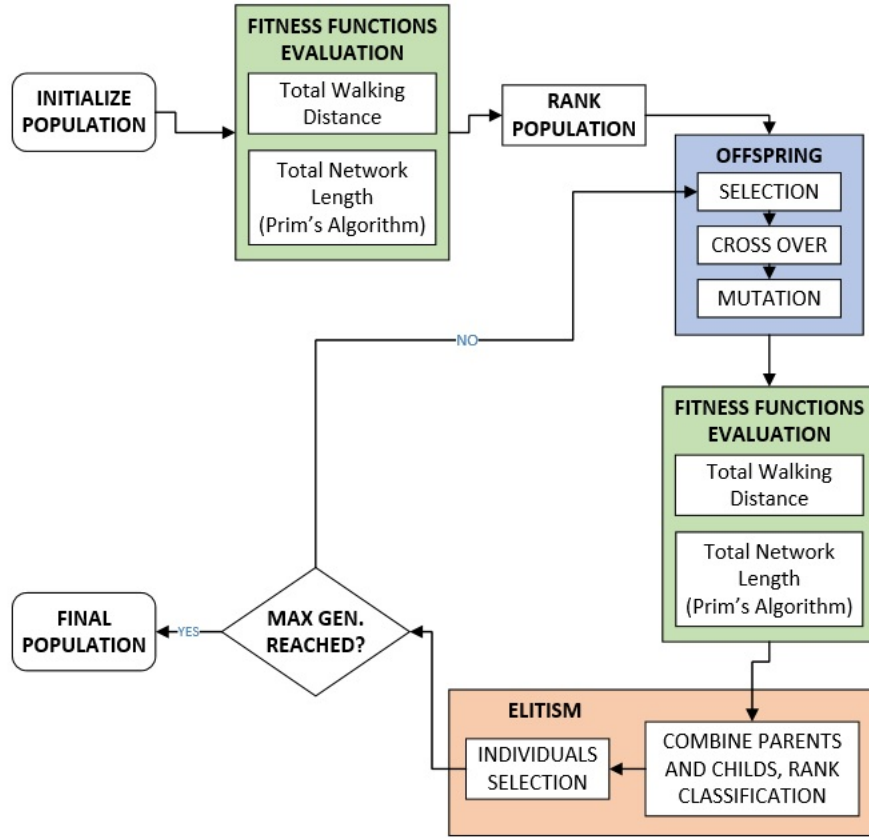


Figure 5.1: Working principle of adapted NSGA-II algorithm

For the case that well is fixed (for Bi-WF), the adapted NSGA-II algorithm seen in above figure is solved once for given well location.

For the case that well location is to be fixed (Bi-WNF), the adapted NSGA-II algorithm is solved for each candidate location in the candidate set. A pool of solutions that are obtained for each candidate location are gathered, and the non-dominated solutions are selected among those.

We assume for both well is fixed and to be fixed case, there is a WDU opened at the same place as the well.

5.2.2 Performance measures

In order to assess the quality of solutions returned by the NSGA-II algorithm we use some performance measures that we will introduce in this section. Whenever possible we use the set of exact Pareto solutions as our reference set and compare the results of the NSGA-II algorithm with this set, using three performance measures, which show the percentage of exact Pareto solutions found and the average and maximum distances from the exact Pareto frontier, respectively.

However, as stated before, for instances with small gamma values, finding exact Pareto solutions in reasonable time was not possible. In such cases we set a time limit and find solutions with a gap. We then compare the solutions returned by the NSGA-II algorithm with this set of approximate Pareto solutions. Since the reference set is also an approximate set, the performance measures that we use in such cases are different. We now discuss the performance measures in detail.

Performance measures for comparing heuristic and exact solution

For $\gamma=80$ and 100, we can find the exact pareto solutions for problem instances where the well location is fixed and to be fixed (given in Appendix B and C). To assess the quality of solutions returned by heuristic algorithm, the following three performance measures [74] are utilized:

- $P\%$: Ratio of nondominated objective vectors returned by NSGA-II;

$$P\% = \frac{|ANS \cap NS|}{|NS|}$$

where: NS represents the exact set of nondominated objective vectors; ANS represents the set of nondominated objective vectors returned by NSGA-II.

In order to consider the closeness of the approximate solutions to their nondominated counterparts, we make use of two distance measures. To state the measures, we assume (O_1^r, O_2^r) is in set NS and (O_1^q, O_2^q) is in set ANS and calculate the following values:

$$R_1 = \max_{(O_1^r, O_2^r) \in NS} O_1^r - \min_{(O_1^r, O_2^r) \in NS} O_1^r$$

(range for the O_1 values in set NS)

$$R_2 = \max_{(O_1^r, O_2^r) \in NS} O_2^r - \min_{(O_1^r, O_2^r) \in NS} O_2^r$$

(range for the O_2 values in set NS)

$$f((O_1^r, O_2^r), (O_1^q, O_2^q)) = \max\{0, \frac{1}{R_1} \cdot (O_1^q - O_1^r), \frac{1}{R_2} \cdot (O_2^q - O_2^r)\}$$

Here, f function takes the zero value, if solutions q and r are the same. Otherwise, it is the maximum component-wise normalized distance between point q and point r .

Using these functions, distance measures are defined as:

- Distance1 (D1): The average distance between the points of set NS and the points in set ANS

$$D1 = \frac{1}{|NS|} \sum_{(O_1^r, O_2^r) \in NS} \min_{(O_1^q, O_2^q) \in ANS} \{f((O_1^r, O_2^r), (O_1^q, O_2^q))\}$$

- Distance2 (D2): The maximum distance between the points of set NS and the points in set ANS

$$D2 = \max_{(O_1^r, O_2^r) \in NS} \left\{ \min_{(O_1^q, O_2^q) \in ANS} \{f((O_1^r, O_2^r), (O_1^q, O_2^q))\} \right\}$$

The smaller the distance values (D1 and D2) are, the better the performance is.

Performance measures for comparing two heuristic solutions (NSGA-II and solutions with gap)

For $\gamma = 60$, finding exact Pareto solutions in reasonable time was not possible. In such cases we set a time limit and find solutions with a gap. We utilize the following methods [75] to check the performance of the solutions returned by the NSGA-II algorithm (ANS) with this set of approximate gapped-Pareto solutions (GNS):

- Spacing (S): The distribution of individuals over the pareto front for a single set (ANS/GNS). This metric measures the standard deviation of pairwise distances.

$$S = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^n (d_i - \bar{d})^2}$$

$$d_i = \min_j \sum_{k=1}^m |O_k^i - O_k^j| \quad i, j = 1, 2, \dots, n$$

where n is the number of nondominated solutions in the ANS (or GNS), m is the number of objectives, in our case it is two and $\bar{d}$ is the mean value of all d_i . When S is equal to zero, it means that all the points are spread uniformly. That is, the ANS/GNS with smaller S value is better.

- Maximum Spread (MS): The maximum extension covered by the nondominated solution set (ANS/GNS), i.e. the maximum euclidean distance between a solution and other nondominated solutions in that set [75]. Mathematically, this is evaluated by using the following equation:

$$MS = \sqrt{\sum_{i=1}^n \max(\|x_i^t - y_i^t\|)}$$

where $\|x_i^t - y_i^t\|$ is the Euclidean distance between solutions x_i and y_i in set ANS (or GNS). The distance of each nondominated solution to all other solutions should be calculated and the maximum of them is noted. n indicates the number of solutions. The more MS value is, the better the solution set is, because higher MS value indicates the solutions are more spread and the set is able to reach further edges of the Pareto front.

- Set coverage (SC): Let Set1 and Set2 are two sets of solution vectors. SC(Set1,Set2) is the ratio of points that are dominated (for two vectors x and y , y dominates x : $y \leq x$) by at least one point in Set1.

$$SC(Set1, Set2) = \frac{|\{x \in Set2 \mid \exists y \in Set1 : y \leq x\}|}{|Set2|}$$

SC(Set1,Set2) can take the value in $[0, 1]$ interval. Both SC(ANS,GNS) and SC(GNS, ANS) values are calculated.

If points in ANS dominate all points in GNS, then by the definition SC(ANS,GNS) equals to 1, while SC(ANS,GNS)=0 implies the opposite. In general, SC(ANS, GNS) and SC(GNS, ANS) both should be considered, as there can be intersections between sets [76]. For instance, SC(ANS, GNS)=1 and SC(GNS, ANS)=0.5 means ANS dominates all point in GNS, but 0.5 of vectors in GNS is the same with ANS. If SC(ANS, GNS)=1 and SC(GNS, ANS)=0, we can say that ANS is better than GNS.

In the literature, the quality of the Pareto solutions are evaluated using three criteria which are defined below [77]:

- Accuracy: To find a set of solutions as close to the Pareto set of solutions as possible. We measure accuracy with Set Coverage measure.
- Diversity: To find a set of solutions as diverse as possible in the Pareto front. We measure diversity of the solutions with Spacing measure.
- Spread: To find a set of solutions which captures the entire spectrum of the Pareto front. We assess spread utilizing Maximum Spread measure.

Chapter 6

The Data Sets

To test the behaviour of the mathematical models and proposed solution methodologies, computational studies are performed. In these studies, data based on refugee camp in Gaziantep, Turkey is used. The required data to be used in the models are as follows:

1. Distance between nodes
2. Threshold value for access
3. Candidate nodes for well locations

This chapter discusses the generation of the data sets and the instances created utilizing this data.

6.1 Distance matrix based on Gaziantep refugee camp



Figure 6.1: View of Syrian Refugee Camp from the top, Gaziantep, Turkey

In our example analysis, we use the distance data of Gaziantep refugee camp, which is established by TRC (see Figure 6.1).

As it has been mentioned earlier in Section 2, the layout of refugee camps are planned based on the standards in the literature. TRC follows the standards of the Sphere Project, in its operations.

According to minimum requirements of Sphere project, there should be fire break areas of a certain length between housings, housing clusters and blocks (the lengths are 2m, 6ms and 15ms for housings, clusters and blocks, respectively). We comply with these the standards of the Sphere project, while generating the point-to-point distance matrix of Gaziantep camp.

We consider each housing cluster as a demand node, in our network. With this assumption and the standards stated above, we create a distance matrix that shows the Euclidean distances between each pair of demand nodes. There are 73 housing clusters (nodes) in Gaziantep refugee camp. The projection plan of the camp can be seen on Figure 6.2. It is not possible to solve the models and find the optimal locations of WDU and water network design for this network with 73 nodes. Hence, we use the middle subset of 73 nodes in the computational studies. This 38-node subset can be seen on the dark-coloured area of projection scheme.

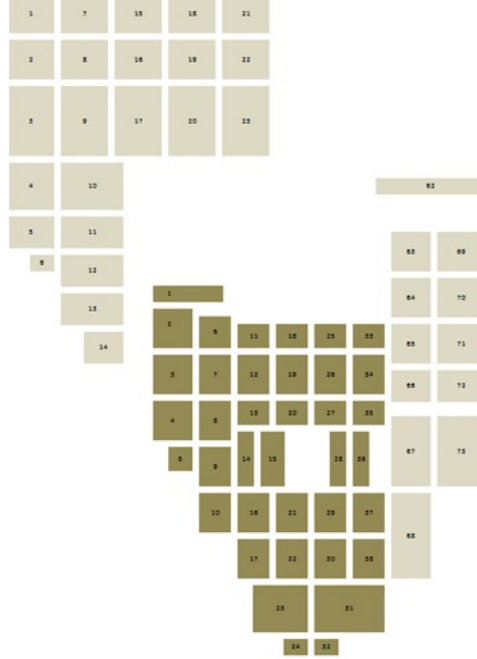


Figure 6.2: Syrian Refugee Camp from the top, Gaziantep, Turkey

6.2 Threshold value for access (γ)

As stated in Section 2.3.1, in almost no camp in the world, WDUs are not placed in every tent. Water need is provided in common use areas such as kitchen, water taps, etc. Therefore, while locating WDUs across the camp, one should ensure that the residents have easy access to these units, which is regulated by some standards provided in the literature.

In the computational studies, we use the standards of UNHCR (Handbook for emergencies, [6]). We take accessibility threshold (γ) value as 60, 70, 80, 90 and 100 for single objective computational studies. For bi-objective models (Bi-WF and Bi-WNF) we set γ value to 60, 80 and 100 in the computational studies.

6.3 Candidate well locations

We generate different candidate well locations to use in the models as input parameters. We firstly categorise the data into two: data for single objective and bi-objective models. The generated data is as follows:

1. For single-objective:

- If well location is fixed, for both objectives (WF-L and WF-D):
We determine ten random candidate well nodes (S). Here, each node S represents the index of housing cluster (which can be seen in Figure 10). The fixed locations of the well can be seen in column S of Table A.1 (in Appendix A).
- If well location is not fixed and to be determined by the models, for two objectives (WNF-L and WNF-D):
We generate a random set of candidate well locations (denoted as S_2). We generate sets S_2 of different cardinality (5, 15 and 25, respectively). Ten random sets are generated for each. The list of these sets S_2 is also given in Table A.1 in Appendix A.

2. For bi-objective:

To obtain bi-objective problem instances, sub-sets of the parameters used in the single-objective problems are used.

- If well location is fixed (Bi-WF):
A 5-element subset of S (denoted as S^b) is used ($S^b \subset S$)
- If well location is to be fixed (Bi-WNF):
Similarly, subsets of S_2 (denoted as S_2^b) are used. We utilize 2 subsets from each type of S_2 (which have 5, 15 and 25 elements).
The list of S^b and S_2^b is also seen in Table A.2, in Appendix A.

6.4 Created Instances

Based on Gaziantep data set, we create instances using various gamma values (accessibility threshold) and candidate well sets, to be utilized in the proposed solution methodologies. As mentioned in Table 4.1, we have six models: two models for the case where the well location is fixed (WF-L and WF-D) and not fixed (WNF-L and WNF-D), and the corresponding bi-objective models (Bi-WF and Bi-WNF).

Using the data sets generated in the previous sub-sections, problem instances are generated. 50 and 150 problem instances are created for WF and the WNF models, respectively. For bi-objective models, less instances are utilized. 15 instances are created for Bi-WF model and 18 instances are used for Bi-WNF model. The summary table of instances is as follows:

Table 6.1: Created instances for models

WF-L & WF-D				Bi-WF			
Well Set	# of Set	γ	# of Inst	Well Set	# of Set	γ	# of Inst
$ S =1$	10	60,70,80, 90,100	50	$ S^b =1$	5	60,80,100	15
WNF-L & WNF-D				Bi-WNF			
Well Set	# of Set	γ	# of Inst	Well Set	# of Set	γ	# of Inst
$ S_2 =5$	10	60,70,80, 90,100	50	$ S_2^b =5$	2	60,80,100	6
$ S_2 =15$	10		50	$ S_2^b =15$	2		6
$ S_2 =25$	10		50	$ S_2^b =25$	2		6

While solving the instances given above, different upper limits for the number of WDUs (p) are defined for different γ values. When $\gamma=60$, p equals to 10, which means models allow up to 10 WDUs to be established. Likewise, when γ is 70, 80, 90 and 100, upper limit p equals to 8, 6, 4 and 3, respectively. As gamma gets larger, we expect a decrease in the number WDUs that will be located, hence decrease the upper limit p .

Chapter 7

Computational Analysis of Single Objective Models

To test the behaviour of the single-objective models, computational studies are performed. Based on Gaziantep data set, the models are solved using various gamma values (accessibility threshold) and candidate well sets. As mentioned in Table 4.1, we have four models for single objective case: two models for the case where the well location is fixed (WF-L and WF-D) and not fixed (WNF-L and WNF-D). This chapter discusses the results obtained from computational experiments of WF and WNF, separately in the following sub-sections.

Using the data sets and instances generated in the previous chapter, the models are solved. As it can be seen in the instance able 6.1, 50 and 150 problem instances are solved for WF and WNF models, respectively using CPLEX.

In order to acquire the optimal solutions of the instances mentioned above, the mathematical models are solved using a PC with Intel Core2Duo T6400 (2.0 GHz) processor, 4GB and CPLEX 12.

7.1 For Fixed Well Location (WF-L and WF-D)

Models of WF-L and WF-D can be solved optimally using CPLEX with the data sets defined in Section 6. The solutions of models WF-L and WF-D can be found in Tables B.1 and B.2 in Appendix B. Solution table for $\gamma=80$ can be seen on Table 7.1 given in the following page.

In the solution tables, instance indices are defined to keep track of sets and parameters used in problems. For example, if we take into consideration instance index `in_80_f1` in Table 7.1, here, 80 means $\gamma = 80$, f1 implies well is fixed and the first well set (S index 1) is utilized for this instance.

In the tables, solutions of the WF-L and WF-D models are provided simultaneously, for the developed data sets. The tables will allow to show the same instances co-existing for different models (WF-L and WF-D), allowing us to analyze about the both edges of Pareto frontier without going through bi-objective solutions.

Table 7.1: Solution analysis of WF-L and WF-D for $\gamma=80$

	WF-L							WF-D						
Instance Index	CPU (h)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
					Total	Average	Max						Average	Max
in_80_f1	0:19:27	308.23	6	6	1552.92	40.87	74.52	0:00:03	1185.10	469.36	6	4	31.19	55.07
in_80_f2	0:06:36	272.73	5	4	1598.63	42.07	74.52	0:00:02	1185.10	443.18	6	4	31.19	55.07
in_80_f3	0:01:55	257.06	6	5	1520.63	40.02	74.52	0:00:02	1185.10	453.49	6	3	31.19	55.07
in_80_f4	0:04:08	263.35	6	5	1552.92	40.87	74.52	0:00:02	1185.10	457.77	6	5	31.19	55.07
in_80_f5	0:03:22	274.93	6	5	1450.36	38.17	74.52	0:00:02	1185.10	449.03	6	5	31.19	55.07
in_80_f6	0:03:39	270.13	6	4	1489.70	39.20	74.52	0:00:03	1185.10	455.92	6	5	31.19	55.07
in_80_f7	0:03:40	260.65	5	4	1600.15	42.11	74.52	0:00:02	1185.10	470.40	6	5	31.19	55.07
in_80_f8	0:06:54	310.23	6	5	1523.48	40.09	74.52	0:00:03	1185.10	493.63	6	6	31.19	55.07
in_80_f9	0:09:00	301.40	6	3	1454.98	38.29	74.52	0:00:02	1185.10	456.43	6	4	31.19	55.07
in_80_f10	0:05:54	281.45	5	4	1686.48	44.38	79.43	0:00:02	1185.10	482.15	6	3	31.19	55.07

The left part of the table shows the results of instances for WF-L model, and the right part shows the results of instances for WF-D model. When the two sides of the table are compared, it is seen that WF-L is solved in much longer time than WF-D. In the table, *Objective of WF-L* column represents value of total network length, and *Objective of WF-D* represents total walking distance.

of WDU columns (under WF-L and WF-D parts) show how many WDUs are established. It can be concluded that the number of WDUs of WF-L is less than that of WF-D. The reason for this is the following: WF-D models aim to reach refugees as much as possible, thus the solutions of WF-D hit upper limit (p) value. On the other hand, the results of WF-L does not necessarily hit the maximum value of p .

Max flow columns show maximum flow coming out of the well. The value of max flow is not dependent on the type of model (WF-L or WF-D). It only gives information on the shape of network. For example, in instance in_80_f1, max flow of WF-L is 6 and max flow of WF-D is 4. Although the *# of WDU's* opened are equal, the shape of networks are different, because the objectives are conflicting. The shapes of the water networks can also be seen on Figures 7.1 and 7.2.

Total, average, maximum distance walked can also be compared in Table 7.1. For example, for instance in_80_f1, maximum distance walked is 74.52 for WF-L model and 55.07 for WF-D. The difference can also be spotted in Figure 7.1 and 7.2.

Note that in WF-D, *# of WDU*, *Objective of WF-D* and the average and maximum distances walked are the same over all the instances in Table 7.1. This is because, for the instances with the same γ value, p 's are also equal and the model locates the WDUs on the same locations. However, since the well location is different in each instance, the model sets up the network from different well locations to the same WDUs. This is why the *Network Length* and *Max flow* values differ across instances.

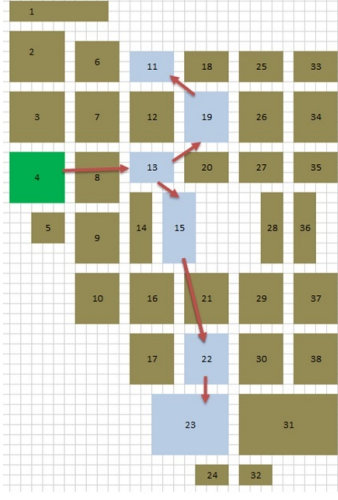


Figure 7.1: Network for WF-L

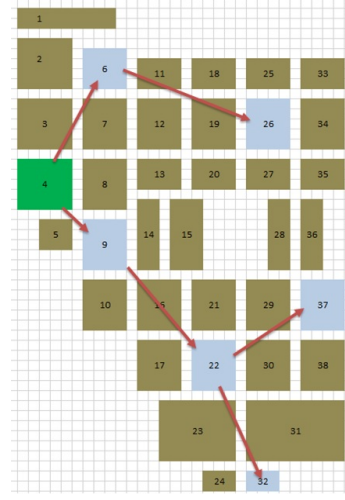


Figure 7.2: Network for WF-D

Figures 7.1 and 7.2 illustrate the layout design of in_80_f1 for both models WF-L and WF-D. On Figure 7.2, WDUs are distributed over the camp to obtain the smallest total walking distance. Contrarily, the WDUs are clustered close to each other to get the minimum network length in WF-L, as seen in Figure 7.1.

For some smaller threshold values, we also observe the total number of nodes walking less than that threshold. We analyze this for two objective functions: WF-L and WF-D. In Table 7.2, consider in_80_f1, the number of nodes walking less than 60 meters is 29, for WF-L. On the other hand, for WF-D, the number of nodes walking increases up to 38. Analysis for other instances can be found in Tables D.1, D.2 in Appendix D.

Table 7.2: Number of nodes walking under thresholds, for $\gamma = 80$ and well fixed

Instance Index	WF-L			WF-D		
	# of nodes walking ≤ 20	≤ 40	≤ 60	# of nodes walking ≤ 20	≤ 40	≤ 60
in_80_f1	6	18	29	8	24	38
in_80_f2	5	16	31	8	24	38
in_80_f3	7	17	30	8	24	38
in_80_f4	6	18	29	8	24	38
in_80_f5	6	21	31	8	24	38
in_80_f6	6	18	30	8	24	38
in_80_f7	5	14	30	8	24	38
in_80_f8	6	19	29	8	24	38
in_80_f9	7	19	31	8	24	38
in_80_f10	5	13	27	8	24	38

Recall that in WF-L, the objective is minimizing network length, and the other objective (total walking distance) is also calculated for the solutions and can be seen under the column of *Total Meters Walked* in Table 7.1. Similarly, when the objective is minimizing total walking distance, total network length also can be seen under *Network Length* column of WF-D. In this way, the points on both edges of the Pareto frontier can be seen and values can be compared for both objectives. We compare the objective function values of both models by percentage. For each γ , we summarize average and maximum percentage difference in the table given below:

Table 7.3: Percent difference of models for well is fixed

γ	WF-L				WF-D			
	Total Network Length		Total Walking Distance		Total Network Length		Total Walking Distance	
	Avr	Max	Avr	Max	Avr	Max	Avr	Max
60	1.00	1.00	1.29	1.38	1.64	1.70	1.00	1.00
70	1.00	1.00	1.42	1.49	1.67	1.79	1.00	1.00
80	1.00	1.00	1.30	1.42	1.66	1.80	1.00	1.00
90	1.00	1.00	1.19	1.28	1.58	1.79	1.00	1.00
100	1.00	1.00	1.17	1.24	1.45	1.74	1.00	1.00

The model of WF-L aims minimizing total network length, thus these columns take 1.00 value (for both average and maximum). Total network length column of WF-D shows how much it increases proportionally, compared to the optimal value of total network length. Same situation is valid for comparing total walking distance values for both models (WF-L and WF-D).

7.2 Well location is to be determined (WNF-L and WNF-D)

After solving and comparing the solutions of models where well is fixed, we solve models for well is not fixed: WNF-L and WNF-D. These models are more difficult to solve than WF models. For smaller γ values and many instances, it takes more than 12 hours to solve, thus we solve models for two hours and take the solutions with gap.

The solutions of models WNF-L and WNF-D can be found in Tables C.1-C.6 in Appendix C. Solutions for the instances with $\gamma=80$ and candidate well sets S_2 ($|S_2|=5$, 15 and 25) can be seen on Table 7.4, in the following page. In that table, instance indexes are defined as follows: in_80_nf5_1 implies $\gamma=80$, nf5 means well is to be fixed and well set S_2 with 5 element is utilized, 1 shows the first set of $|S_2|=5$ is used.

Table 7.4: Solution analysis of WNF-L and WNF-D for $\gamma=80$ and $|S_2|=5, 15$ and 25

	WNF-L								WNF-D						
Instance Index	CPU (h)	Gap (%)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
						Total	Avg	Max						Avg	Max
in_80_nf5_1	2:00:13	58.01	244.95	6	3	1552.92	40.87	74.52	0:00:01	1185.10	430.77	6	4	31.19	55.07
in_80_nf5_2	1:04:11	opt	244.95	6	4	1552.92	40.87	74.52	0:00:02	1185.10	449.03	6	5	31.19	55.07
in_80_nf5_3	9:51:51	opt	244.95	6	3	1552.92	40.87	74.52	0:00:03	1185.10	436.65	6	4	31.19	55.07
in_80_nf5_4	2:27:13	opt	252.94	6	3	1559.26	41.03	74.52	0:00:01	1185.10	449.03	6	5	31.19	55.07
in_80_nf5_5	9:53:54	opt	244.95	6	5	1552.92	40.87	74.52	0:00:05	1185.10	449.03	6	5	31.19	55.07
in_80_nf5_6	0:24:06	opt	244.95	6	3	1552.92	40.87	74.52	0:00:01	1185.10	436.65	6	4	31.19	55.07
in_80_nf5_7	17:30:57	opt	270.13	5	4	1686.48	44.38	79.43	0:00:02	1185.10	449.03	6	4	31.19	55.07
in_80_nf5_8	9:03:30	opt	244.95	6	4	1552.92	40.87	74.52	0:00:01	1185.10	440.37	6	4	31.19	55.07
in_80_nf5_9	3:24:20	opt	244.95	6	3	1552.92	40.87	74.52	0:00:01	1185.10	453.06	6	3	31.19	55.07
in_80_nf5_10	3:53:23	opt	244.95	6	5	1552.92	40.87	74.52	0:00:01	1185.10	443.18	6	4	31.19	55.07
in_80_nf15_1	2:00:11	30.93	244.95	6	5	1552.92	40.87	74.52	0:00:03	1185.10	430.77	6	4	31.19	55.07
in_80_nf15_2	2:00:12	45.94	244.95	6	3	1552.92	40.87	74.52	0:00:02	1185.10	430.77	6	4	31.19	55.07
in_80_nf15_3	2:00:23	23.46	244.95	6	5	1552.92	40.87	74.52	0:00:04	1185.10	440.37	6	4	31.19	55.07
in_80_nf15_4	2:00:10	62.50	244.95	6	4	1552.92	40.87	74.52	0:00:04	1185.10	436.65	6	4	31.19	55.07
in_80_nf15_5	2:00:25	32.00	244.95	6	3	1552.92	40.87	74.52	0:00:05	1185.10	449.03	6	5	31.19	55.07
in_80_nf15_6	2:00:26	50.93	244.95	6	5	1552.92	40.87	74.52	0:00:03	1185.10	430.77	6	4	31.19	55.07
in_80_nf15_7	2:00:10	32.96	244.95	6	5	1552.92	40.87	74.52	0:00:02	1185.10	430.77	6	4	31.19	55.07
in_80_nf15_8	2:00:25	38.25	244.95	6	5	1552.92	40.87	74.52	0:00:03	1185.10	430.77	6	4	31.19	55.07
in_80_nf15_9	0:04:40	opt	244.95	6	4	1552.92	40.87	74.52	0:00:03	1185.10	430.77	6	4	31.19	55.07
in_80_nf15_10	0:05:56	opt	244.95	6	4	1552.92	40.87	74.52	0:00:05	1185.10	440.37	6	4	31.19	55.07
in_80_nf25_1	0:09:05	opt	244.95	6	4	1552.92	40.87	74.52	0:00:06	1185,1	430,77	6	4	31.19	55.07
in_80_nf25_2	2:00:25	28.85	244.95	6	4	1552.92	40.87	74.52	0:00:05	1185,1	440,37	6	4	31.19	55.07
in_80_nf25_3	2:00:10	44.85	244.95	6	4	1552.92	40.87	74.52	0:00:03	1185,1	430,77	6	4	31.19	55.07
in_80_nf25_4	2:00:26	39.25	244.95	6	4	1552.92	40.87	74.52	0:00:05	1185,1	430,77	6	4	31.19	55.07
in_80_nf25_5	2:00:25	45.22	244.95	6	4	1552.92	40.87	74.52	0:00:02	1185,1	440,37	6	4	31.19	55.07
in_80_nf25_6	2:00:23	30.98	244.95	6	4	1552.92	40.87	74.52	0:00:07	1185,1	436,65	6	4	31.19	55.07
in_80_nf25_7	1:00:21	opt	244.95	6	4	1552.92	40.87	74.52	0:00:02	1185,1	430,77	6	4	31.19	55.07
in_80_nf25_8	2:00:28	58.81	244.95	6	4	1552.92	40.87	74.52	0:00:08	1185,1	436,65	6	4	31.19	55.07
in_80_nf25_9	2:00:27	49.28	244.95	6	4	1552.92	40.87	74.52	0:00:03	1185,1	436,65	6	4	31.19	55.07
in_80_nf25_10	0:09:28	opt	244.95	6	4	1552.92	40.87	74.52	0:00:04	1185,1	430,77	6	4	31.19	55.07

The observations that we make based on the results reported in Table 7.4 are similar to the ones that we make for the "fixed-well" case. Additionally, in WNF tables, there is a *Gap (%)* column under WNF-L.

For $\gamma=80$ and $|S_2|=5$ instances, nine optimal solutions are found, except one instance, this unsolvable instance got stuck at 58 % gap. The other instances are solved even though it takes a long time, approximately 57.5 hours to solve. For $|S_2|=15$, two instances are solved optimally, other eight instances are solved with average 36 % and maximum 62.5 % gap. Similarly, For $|S_2|=25$, three instances are solved optimally, other seven instances could be solved with approximately average of 43 and maximum 58.81 % gap. Similar situation is observed for $\gamma=60$ and 70 in Appendix C.

As in the analysis of WF instances, we can see the solutions at both edges of the Pareto front, in the solution analysis of WNF (both in Table 7.4 and Appendix C). In this way, before passing on to bi-objective solutions, we can compare both edges of Pareto and find percent increase of objectives from its optimal values. We summarize average and maximum percentage difference for different γ and well sets in Table 7.5.

Table 7.5: Percent difference of models for well is to be fixed

		WNF-L				WNF-D			
		Total Network Length		Total Walking Distance		Total Network Length		Total Walking Distance	
	γ	Avr	Max	Avr	Max	Avr	Max	Avr	Max
$ S_2 =5$	60	1.00	1.00	1.33	1.36	1.72	1.80	1.00	1.00
	70	1.00	1.00	1.47	1.49	1.86	1.99	1.00	1.00
	80	1.00	1.00	1.32	1.42	1.87	2.02	1.00	1.00
	90	1.00	1.00	1.22	1.28	1.83	1.96	1.00	1.00
	100	1.00	1.00	1.21	1.24	1.75	2.06	1.00	1.00
$ S_2 =15$	60	1.00	1.00	1.32	1.34	1.66	1.71	1.00	1.00
	70	1.00	1.00	1.51	1.52	1.81	1.82	1.00	1.00
	80	1.00	1.00	1.31	1.31	1.78	1.83	1.00	1.00
	90	1.00	1.00	1.24	1.24	1.67	1.73	1.00	1.00
	100	1.00	1.00	1.20	1.21	1.58	1.67	1.00	1.00
$ S_2 =25$	60	1.00	1.00	1.31	1.34	1.65	1.67	1.00	1.00
	70	1.00	1.00	1.50	1.52	1.80	1.83	1.00	1.00
	80	1.00	1.00	1.31	1.31	1.77	1.80	1.00	1.00
	90	1.00	1.00	1.24	1.24	1.67	1.71	1.00	1.00
	100	1.00	1.00	1.21	1.21	1.56	1.58	1.00	1.00

In the table, it is observed that for WNF-D and well set $|S_2|=5$, average and maximum percentage difference of total network length is higher than $|S_2|=15$ and 25. This situation can be interpreted as follows, when the number of candidate locations for the well increases, the model can choose the well which gives the shorter network length. It can be concluded that, in WNF-D models, if candidate well location increases, the other criterion i.e. total network length gets better values.

In WNF-L, the percentage increment of total walking distance does not change according to cardinality of well sets. Thus, we can infer that, total walking distance, consequently, the locations of WDUs are not depended to the cardinality of well sets. On the other hand, the percent difference of total walking distance declines as γ value increases for three cases ($|S_2|=5$, 15 and 25). But we can not generalize, because this status is disrupted by $\gamma=70$, the reason for the disruption may be caused by the layout i.e. the distance matrix.

Chapter 8

Computational Analysis of Bi-Objective Models

When the single-objective models are solved using CPLEX, it is realized that: WF-L and WF-D are easier to solve, which makes sense because models WF-L and WF-D are simpler than WNF-L and WNF-D.

Additionally, it is observed that as γ value is reduced, problems of WF-L and WNF-L (objective of minimizing total network length) become harder to solve. But it is not the case for objective of minimizing total walking distance. The main reason why WF-L and WNF-L models take too long to solve is as follows: when γ value is decreased, more WDUs should be used in order to make the problem feasible (i.e. to satisfy the accessibility threshold constraint). The combinations of different locations of WDUs leads to different network designs. If the number of WDUs increases, number of solution combination also increments and feasible solution set builds up. This leads to increasing computational time.

On the other hand, when objective is minimizing total walking distance, the problem focuses on locating the WDUs, not on the network design between these WDUs.. Thus its computational time is quite short. Given the dataset, all instances are solvable in less than ten seconds.

Bi-objective models are solved with CPLEX using the instances defined in the previous section in Table 6.1. Recall that, 15 instances are created for Bi-WF model and 18 instances are used for Bi-WNF model. These bi-objective models are solved both using CPLEX and NSGA-II.

For $\gamma=80$ and 100 optimal pareto solutions are found for Bi-WF and Bi-WNF models. For $\gamma=60$, which results in more difficult instances, models are solved for ten minutes and solutions are noted with gap. The bi-objective models are also solved using NSGA-II and the results are assessed using the performance measures. Similar to the previous chapter, the well fixed (Bi-WF) and well is to be determined (Bi-WNF) cases are analysed separately.

8.1 Bi-WF

Because models are solved optimally for $\gamma=80$ and 100, and solved with gap for $\gamma=60$, they are discussed in different tables. Comparative summary table of optimal and heuristic solutions for Bi-WF for $\gamma=80$ and 100 is given below.

Table 8.1: Summary table of Bi-WF for $\gamma=80$ and 100

	Epsilon Constraint Approach						NSGA-II					
	# of NS			CPU Time (sec)			# of ANS			CPU Time (sec)		
γ	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
80	23	26	29	9662	14500.4	20508	23	25.4	29	1	1	1
100	2	4.2	8	1.7	4.6	7.7	2	4.2	8	1	1	1

In the table, *# of NS* means number of non dominated solutions returned by the epsilon-constraint method. *# of ANS* means number of approximate non dominated solutions returned by NSGA-II. Minimum, average and maximum number of pareto solutions and solution times of five instances are given in the table. It is clearly seen that, solution times of epsilon constraint method are considerably long, for $\gamma=80$. In order to check performance of NSGA-II, we use the performance measures defined in Section 5.2. The performance measures are seen in Table 8.2.

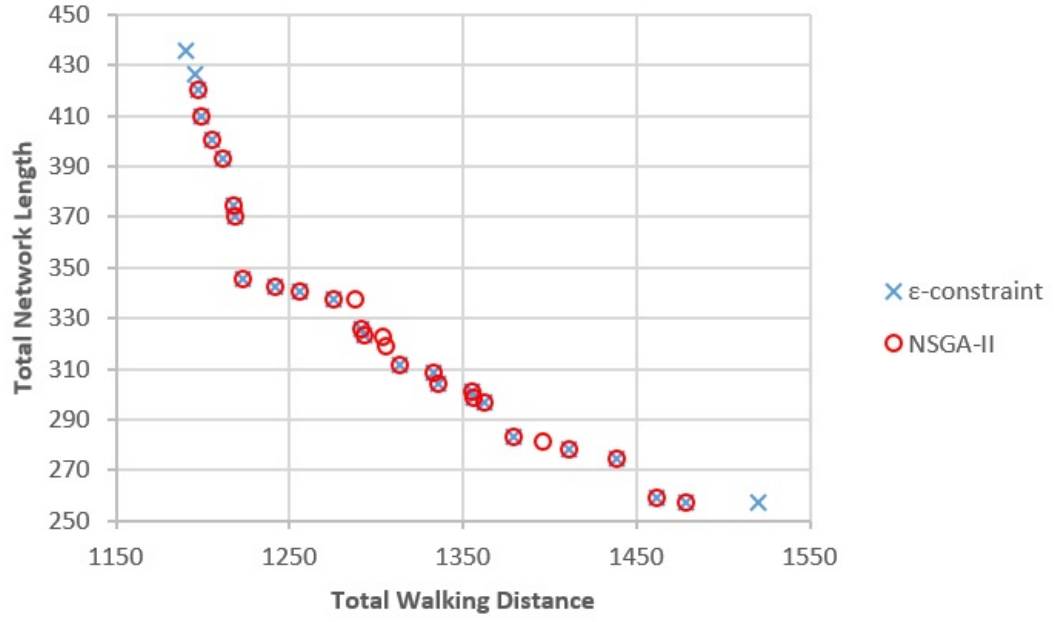
Table 8.2: Performance measures of Bi-WF for $\gamma=80$ and 100

γ	P%			D1			D2		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
80	66.667	88.718	100.000	0	0.002	0.004	0	0.018	0.063
100	100.000	100.000	100.000	0	0	0	0	0	0

For $\gamma=100$, minimum, average and maximum values of P% (ratio of non dominated vectors returned by NSGA-II) are equal to 100, which means NSGA-II is able to find all pareto optimal solutions. Therefore, average and maximum distances (D1 and D2) between the points NS and ANS are zero.

For $\gamma=80$, NSGA-II finds 89 % of the exact solutions, on average. Similarly, maximum percentage P% is 100, which means there are instance(s) that NSGA-II could find the whole set of exact solutions. The minimum value of P% is 67.

To give an idea on the scale of the distance measure used, we provide the results for an example instance with $\gamma=80$. In this instance P%, D1 and D2 values are 88.462, 0.003 and 0.063 respectively. We draw a pareto chart to visualise the solutions both found by epsilon-constraint and NSGA-II, and the performance measures P%, D1, D2 values which are seen as follows:



For $\gamma=60$, each single objective model in the epsilon constraint approach is solved for ten minutes, the solutions are reported with the corresponding optimality gaps.

Table 8.3: Summary table of Bi-WF for $\gamma=60$

	Epsilon Constraint Approach (with gap)			NSGA-II		
	Min	Avg	Max	Min	Avg	Max
# of GNS/ANS	6	10.8	21	21	30	48
CPU Time (sec)	1993	5397	11471	1	1	1
Average Gap (%)	0.96	2.17	3.43	-	-	-

In the table, # of GNS means the number of non dominated approximate pareto solutions with gap returned by epsilon-constraint method. Similarly, # of ANS is the number of approximate non dominated solutions returned by NSGA-II algorithm. Minimum, average and maximum # of GNS, # of ANS, average gap and total solution times of five instances are given in the table.

The minimum, average and maximum # of GNS is pretty less than # of ANS. The reason for this is because the models are solved for ten minutes, if time limit is exceeded and no integer solution is found, then epsilon constraint algorithm is stopped. It is also clearly seen in Table 8.3, although there are far fewer solutions in epsilon constraint method, solution times are considerably long.

In order to compare the performance of NSGA- II and solutions with gap, we use performance measures stated in Section 5.2. The performance measures are seen on Table 8.4.

Table 8.4: Performance measures of Bi-WF for $\gamma=60$

Measures	Epsilon Constraint Approach (with gap)			NSGA-II		
	Min	Avg	Max	Min	Avg	Max
S	5.04	9.88	15.42	3.90	10.08	15.94
MS	1.90	2.76	3.49	5.17	5.78	6.98
SC(GNS,ANS)	0.04	0.24	0.95	-	-	-
SC(ANS,GNS)	-	-	-	0.29	0.60	1.00

In the table, Spacing (S) and Maximum Spread (MS) metrics analyze observed pareto(s) individually, hence they are not comparative.

S metric measures the deviation distance from the average solution, which is higher in NSGA-II than epsilon constraint. The reason for this can be the following: the number of GNS is fewer and epsilon constraint approach can only find a limited part of the pareto frontier, thus the deviation (S) is lower. Another diversity metric MS is also higher in NSGA-II, which can be explained with the same reason.

Set Coverage (SC) is a comparative analysis which measures the ratio of (weakly) domination by the other set. SC metrics show how better an algorithm is than the other. The closer the SC value to 1, the better the solution is. If points in ANS dominate all points in GNS, then by the definition $SC(ANS, GNS)$ equals to 1, but this information alone is not enough to compare ANS and GNS. Both $SC(ANS, GNS)$ and $SC(GNS, ANS)$ values should be considered to determine which one of ANS or GNS is better, because there can be intersections between the two sets. For example, in Table 8.4 $\max SC(ANS, GNS)=1$ which means points in ANS dominate all points in GNS. However, minimum value of $SC(GNS, ANS)$ is not equal to zero, that is due to common elements of two sets. Overall, minimum, average and maximum values of NSGA-II ($SC(ANS, GNS)$) are higher.

To give an idea on the scale of the S, MS and SC metrics used, we provide a pareto chart for an example instance with $\gamma=60$. In this instance, S, MS and $SC(GNS, ANS)$ values for epsilon constraint approach are 9.65, 2.81 and 0.04, and for NSGA-II S, MS and $SC(ANS, GNS)$ are 10.03, 5.38 and 0.29, respectively. For this instance, S and MS values obtained by epsilon constraint and NSGA-II are close to the average values. $SC(ANS, GNS)$ and $SC(GNS, ANS)$ are the minimum values in Table 8.4.

The pareto chart in Figure 8.2 visualises the GNS and ANS both found by epsilon-constraint and NSGA-II.



Figure 8.2: Comparison of GNS and ANS, for an instance of $\gamma=60$

In the pareto chart, it can be realized that the GNS points (blue crosses) are clustered at a certain area: minimizing total walking distance edge of the pareto. Because the epsilon constraint algorithm starts from this edge, which is considerably easier to solve, problem became harder to solve after few iterations, and no integer solution is found in a given time limit, thus the algorithm stops. Recall that, for WF-L model and $\gamma=60$, we also could not able to solve models in reasonable times, thus take the solutions with gap (see Table B.1 in Appendix B)

The solutions of GNS is not able to capture the entire spectrum of the Pareto frontier. The spread of ANSs is fairly higher than GNS, which makes MS value of NSGA-II almost two times of the epsilon constraint approach. The diversity of GNSs is much less than ANSs (red circles), which make sense because S value of epsilon constraint approach are less than S value of NSGA-II.

$SC(GNS, ANS)=0.04$ means 4 % of GNS can dominate the set of ANS. Likewise, $SC(ANS, GNS)$ is 0.29 implies 29 % of ANS can dominate solutions of GNS. As can be seen in the graph, the cardinality of GNS is 7, and two solutions of GNS are dominated by ANS. Thus, $SC(ANS, GNS)=2/7$ (0.29).

To say that the epsilon constraint yields worse results than NSGA-II, it is not enough that the SC(GNS, ANS) value is lower. The SC(ANS, GNS) also should be close to 1. Thus, we can not say that NSGA-II gives significantly better pareto solutions than the epsilon constraint approach, for this instance.

In order to find more spread solutions, especially on the minimizing total network length side of the Pareto front, we re-implement the epsilon constraint approach (with gap) with some modifications. Firstly, we increase the time limit from 10 to 30 minutes for each iteration and the step size k value from 0.1 to 10. However, we observe the same situation: the termination of the algorithm after few iterations. We summarise the results in Table 8.5.

Table 8.5: Summary table of Bi-WF for $\gamma=60$ (Time limit=30 min and $k=10$)

	Epsilon Constraint Approach (with gap)		
	Min	Avg	Max
# of GNS	4	5.8	7
CPU Time (sec)	3700	7625.8	10458
Average Gap (%)	1.69	2.08	2.45

In the table above, the solution times are higher than in Table 8.3, but the number of GNS is less. Increasing the timelimit does not help finding more and spread solutions.

We also attempt to solve the models starting from the other edge of the Pareto, i.e. minimizing total network length, in order to find solutions on this part of the Pareto frontier. However, the models are not solved optimally in 12 hours (This is also seen in the single objective model results shown in Appendix B).

8.2 Bi-WNF

Similar to the Bi-WF case, the Bi- WNF problem instances with γ values 80 and 100 are analysed in various tables and using different performance measures from $\gamma=60$ case, because $\gamma=80$ and 100 models are solved optimally, $\gamma=60$ models are solved with gap.

While analyzing Bi-WNF, instead of giving the minimum, average and maximum number of solutions and solution times (as in Table 8.1), we handle the instances one by one, in Table 8.6. Our purpose in doing so is, to show that, the solution times of different cardinality of well sets also differ, for epsilon constraint approach. It can be seen in Table 8.6, as the cardinality increases, the solution times increase, which is more remarkable when $\gamma=80$. The average solution times for instances with the well set cardinality of 5, 10 and 15 are 5, 15 and 25, are 44721.5, 91351 and 152219.5, respectively (for $\gamma=80$ and epsilon constraint approach).

Table 8.6: Solution table of Bi-WNF for $\gamma=80$ and 100

γ	Set	Epsilon Constraint Approach		NSGA-II	
		# of NS	CPU Time (sec)	# of ANS	CPU Time (sec)
80	$ S_2^b =5$	38	50283	38	5
		36	39160	35	5
	$ S_2^b =15$	39	81536	38	15
		38	101166	38	15
	$ S_2^b =25$	38	135016	38	25
		38	169423	38	25
100	$ S_2^b =5$	11	13	10	5
		6	6	5	5
	$ S_2^b =15$	11	18	11	15
		6	7	5	15
	$ S_2^b =25$	11	22	11	25
		11	19	10	25

It can be seen in the table that, the solution times of NSGA-II also increase, as cardinality of well sets increases. The reason is, for example, for cardinality of 5, NSGA-II algorithm is run five times, and the approximate solution times (1 sec) is multiplied by 5.

Besides solution times, the number of NS and ANS increases as γ decreases.

In order to compare the performances of NSGA-II and epsilon constraint approach, we use performance measures P%, D1 and D2, which are seen on Table 8.7. Regardless of the cardinality of well sets, we show the minimum, average and maximum values of P%, D1 and D2 that have the same γ value in this table.

Table 8.7: Performance measures of Bi-WNF for $\gamma=80$ and 100

γ	P%			D1			D2		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
80	87.179	96.011	100	0	0.0001	0.0003	0	0.0016	0.0095
100	83.333	91.414	100	0	0.0089	0.0450	0	0.0551	0.2701

For $\gamma=80$, NSGA-II finds on average 96 % of the exact solutions, which demonstrates that the algorithm works very well for these instances. Similarly, maximum percentage P% is 100, which means there are instance(s) that NSGA-II could find the whole pareto optimal solutions. The minimum value of P% is 87, again a desirable percentage. Therefore, average and maximum distances (D1 and D2) between the points NS and ANS are fairly small values close to zero.

For $\gamma=100$, average value of P% is equal to 91.4. It can be realised that the percentage is higher for $\gamma=80$, than $\gamma=100$, thus the distance values (D1 and D2) are higher for $\gamma=100$.

For $\gamma=60$, we report minimum, average and maximum number of solutions found and solution times in Table 8.8. Similar to the Bi-WF case, each single objective model in the epsilon constraint approach is solved for 600 seconds, and the solutions are reported with the corresponding optimality gaps. In Table 8.8 we do not categorize the solutions by the cardinality of well sets (as in Table 8.6 for $\gamma=80$ and 100). The reason of this is because we have not observed a significant change in *# of GNS/ANS* and solution times for different cardinality levels.

Table 8.8: Summary table of Bi-WNF for $\gamma=60$

	Epsilon Constraint Approach (with gap)			NSGA-II		
	Min	Avg	Max	Min	Avg	Max
# of GNS/ANS	7	8.5	11	34	37.7	41
CPU Time (sec)	5435	6193.8	7014	5	15	25
Average Gap (%)	0.85	1.87	2.42	-	-	-

In Table 8.8, the minimum, average and maximum *# of GNS* are also quite less than *# of ANS*, as in the Bi-WF case. Although far fewer solutions are found, minimum, average and maximum *CPU Times* of epsilon constraint method are considerably longer than NSGA-II.

To assess the performance of NSGA- II and solutions with gap, we use S, M and SC metrics and the performance measures are seen on Table 8.9.

Table 8.9: Performance measures of Bi-WNF for $\gamma=60$

Measures	Epsilon Constraint Approach (with gap)			NSGA-II		
	Min	Avg	Max	Min	Avg	Max
S	5.21	11.22	17.10	5.07	6.64	8.84
MS	2.97	3.14	3.49	6.06	6.32	6.62
SC(GNS,ANS)	0.05	0.09	0.19	-	-	-
SC(ANS,GNS)	-	-	-	0.25	0.60	0.78

Opposite to the Bi-WF case, here, diversity metric S is higher in epsilon constraint approach than NSGA-II. The reason can be the following: the solutions of ANS are close together while solutions of GNS are distant from each other.

MS metric is on average two times higher in NSGA-II than epsilon constraint approach, which means the normalized maximum euclidean distance between two points in NSGA-II is two times higher than solutions found by the epsilon constraint approach. This makes sense because the number of solutions is almost four times more in NSGA-II, for this reason, the normalized distance i.e. maximum spread is higher.

The minimum, average and maximum values of SC metric are much higher in NSGA-II than epsilon constraint, which implies more accuracy of ANS solutions.

8.3 NSGA-II Solutions for 73 Nodes

In this section, we solve the bi-objective models for all nodes in Gaziantep refugee camp (i.e. $n=73$, see Figure 6.2) with adapted NSGA-II. We consider γ values as 60, 70, 80, 90 and 100. Since number of nodes are approximately doubled, the upper limit for WDUs (i.e. p) is also approximately doubled. We set p as 20, 16, 12, 10 and 8 for $\gamma=60, 70, 80, 90$ and 100, respectively. Similar to the 38-node setting, we use 5 and 6 instances for well is fixed and well is to be fixed cases, respectively. We summarize the results in Table 8.10 for well is fixed case.

Table 8.10: Summary of NSGA-II solutions for 73 nodes and well is fixed case

γ	NSGA-II					
	# of ANS			CPU Time (sec)		
	Min	Avg	Max	Min	Avg	Max
60	50	61.2	67	45	45	45
70	63	75.4	92	40	40	40
80	35	41.8	47	4	4	4
90	19	23.4	28	4	4	4
100	16	25.4	38	3	3	3

Similar to the 38-node setting, we observe that, as γ decreases, the solution time increases. The number of solutions (*# of ANS*) also tends to increase as γ decreases, with a few exceptions.

We choose one instance for γ values 60, 80 and 100 and depict the Pareto frontiers in Figure 8.3. We choose the instances for which the number of (*ANS*) solutions is close to the average values represented in Table 8.10.

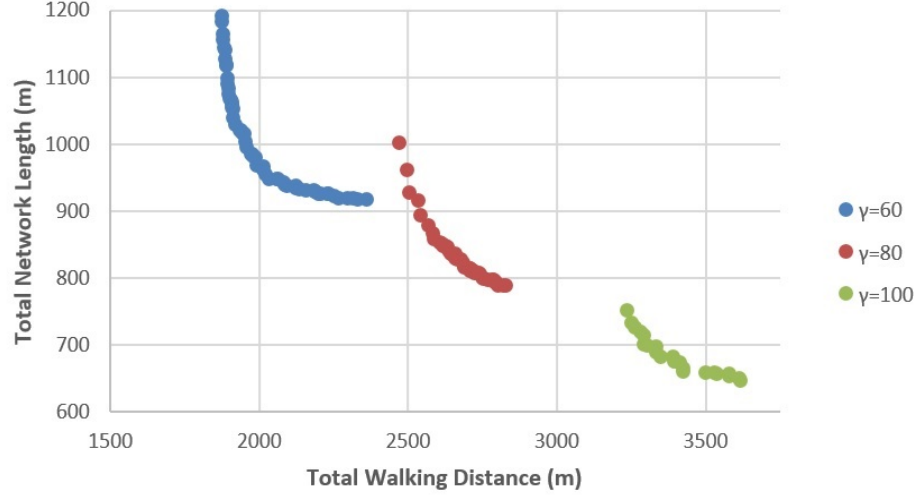


Figure 8.3: Comparison of an instance for 73 nodes

We observe that, as γ increases, the number of WDUs (p) decreases, thus the network structure gets simplified and the total network length becomes smaller. On the other hand, total walking distance gets higher. This is expected since γ parameter implicitly controls the total walking distance.

To be more precise, for $\gamma=60$, p equals to 20 and the minimum total walking distance on the Pareto frontier is 1875.37 and the network length is 1190.97. When γ increases to 80, p decreases to 12 and the minimum total walking distance on the Pareto increases to 2473.41 and the network length decreases to 1001.74. Similarly, for $\gamma=100$, 8 WDUs are opened and the minimum total walking distance increases to 3238.47 and the network length decreases to 751.37.

Additionally, when the solutions on a Pareto move towards the minimizing total walking distance edge, the solutions get closer to the smaller γ value.



Figure 8.4: $\gamma=60$: The minimum total walking distance

Figure 8.5: $\gamma=60$: An Alternative Network

Figures 8.4 and 8.5 illustrate the layout design of an instance for $\gamma=60$. Figure 8.4 represents the solution with optimum walking distance value (1875.37), which also has the longest network length: 1190.97. In this figure, WDUs are more distributed over the camp to obtain the smallest total walking distance. Figure 8.5 shows an intermediate solution, whose objective of total walking distance value is 1958.95 and the network length is 993.96. As can be interpreted from the objective values, 84.58 (4.5%) meters decrease of total walking distance will earn 196.04 (16%) unit cost.

For well is not fixed case, 6 new instances are created (2 instances for each cardinality level of the well sets (5,15,25)). Here S'_2 represents the set of randomly selected candidate well locations and $|S'_2|$ represents the cardinality. The results are shown in Table 8.11.

Table 8.11: Summary of NSGA-II solutions for 73 nodes and well is to be fixed case

γ	Set	NSGA-II	
		# of ANS	CPU Time (sec)
60	$ S'_2 =5$	71	225
		67	225
	$ S'_2 =15$	87	675
		94	675
	$ S'_2 =25$	101	1125
		97	1125
70	$ S'_2 =5$	39	200
		42	200
	$ S'_2 =15$	113	600
		104	600
	$ S'_2 =25$	110	1000
		94	1000
80	$ S'_2 =5$	52	20
		53	20
	$ S'_2 =15$	63	60
		48	60
	$ S'_2 =25$	67	100
		73	100
90	$ S'_2 =5$	32	20
		29	20
	$ S'_2 =15$	39	60
		45	60
	$ S'_2 =25$	39	100
		46	100
100	$ S'_2 =5$	33	15
		32	15
	$ S'_2 =15$	37	45
		47	45
	$ S'_2 =25$	44	75
		46	75

As it can be seen from the table, as the cardinality of S'_2 increases, solution times of NSGA-II also increases. Again, smaller γ values lead to higher solution times.

Chapter 9

Conclusion

In this study, we aim to address the refugee camp management problem and approach one of its sub-problems: the bi-objective water network design problem in refugee camps from the OR perspective.

Our main motivation is to provide an overall framework for the general refugee camp management problem. The related literature is very scarce and diverse. Utilizing TRCs know how from the field, our aim in Chapter 2 is to link the OR literature with the different phases of camp management. We differentiate the decisions based on their levels as strategic (constituting the establishment phase) and tactical and operational which are discussed in the administration phase. We also highlight main challenges and dynamics of the decision making problems encountered in different parts of the proposed framework, which may constitute many various problems to the OR literature each of which can open new venues for future research.

One of the new venues explained in the establishment phase of the framework is water distribution network design in refugee camps. In Chapter 3, we define this problem. In Chapter 4, we propose single and bi-objective models that determine the locations of the water well and WDUs and design general network structure by taking relevant constraints (threshold for access) and multiple objectives into account.

In Chapter 5, the exact and heuristic solution methodologies are proposed to solve bi-objective models. To find the exact pareto front, we utilize the epsilon constraint method. For smaller threshold distances (gamma values), each iteration of the epsilon constraint method takes notably long time to solve. Therefore, we use a customized version of NSGA-II algorithm. In order to compare the quality of pareto solutions returned by NSGA-II and the epsilon constraint method, we apply performance measures from the literature.

Chapter 6 presents the data sets and instances created to observe the behaviour of the proposed solution methodologies. Utilizing the instances defined in Chapter 6, computational analyses of single-objective models are discussed in Chapter 7. The results of WF-L and WF-D are presented comparatively. In this way, two extreme points of bi-objective pareto frontier are observed. Similar analyses are also conducted for well to be fixed cases: WNF-L and WNF-D. It is also noticed that the models of WF-L and WNF-L are harder to solve and solution times are considerably longer compared to WF-D and WNF-D, especially for smaller gamma values.

In Chapter 8, computational analysis of bi-objective models are presented. The minimum, average and maximum number of pareto solutions obtained from epsilon-constraint and NSGA-II and their total solution times are provided. It can be observed that the number of solutions obtained from the epsilon constraint approach and NSGA-II are close to each other, except the number of solutions returned via epsilon constraint with gap. If we compare the solution times, solution times of the epsilon constraint approach is quite longer than NSGA-II. In addition, as gamma value decreases, the solution times of the epsilon constraint method increase, as expected.

Chapter 8 also includes the performance comparison studies of the epsilon constraint method and NSGA-II. The solutions returned from both algorithms are assessed utilizing the performance measures from the literature. Whenever possible we assess the performance of NSGA-II with respect to the exact Pareto set. In cases where the exact Pareto set could not be found to in reasonable time, we use the epsilon constraint approach in a heuristic manner, solving each model with a gap and compare the results with those of the NSGA-II. As a result, it is observed that NSGA-II algorithm performed better, for all measures.

To the best of our knowledge, our study offers the first framework of the refugee camp management problem, as well as the clean water distribution network in refugee camps.

As future research, this study can be extended in many directions. One possible extension would be considering the third objective on utilization of WDUs. In addition, the problem cannot be solved for bigger data sets. Thus, exact algorithms could be improved to solve larger problems in reasonable time. Or, alternative heuristic solution methodologies can be implemented such as the Strength Pareto Evolutionary Algorithm (SPEA-II). Another research direction worth exploring is considering other components of the water network such as water storage units (tanks, depots etc.) between wells and WDUs, which leads to more extensive problems.

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Appendix A

Data

Table A.1: List of candidate well locations for single objective models

#	WF-L & WF-D S	WNF-L & WNF-D		
		$ S_2 =5$	$ S_2 =15$	$ S_2 =25$
1	4	6,12,13,26,31	2,3,6,7,8,11,12,13,18,29,30,31,36,37,38	1,2,3,5,6,7,8,10,12,13,14,16,17,19,20,22,24,25,27,28,29,31,32,35,37
2	7	4,19,26,29,38	2,6,8,9,12,13,14,15,16,21,28,31,34,35,36	1,3,4,5,7,8,9,11,13,14,16,18,19,21,22,24,25,26,29,34,30,31,35,36,38
3	14	11,13,19,22,29	4,5,6,8,14,15,16,19,20,21,23,26,30,31,34	2,3,5,6,7,8,9,10,11,12,14,15,16,17,20,22,24,26,28,29,30,32,33,34,36
4	18	14,20,24,26,32	2,5,6,7,9,10,11,13,16,18,19,24,32,34,35	1,2,4,6,7,8,9,12,15,16,17,18,19,20,21,22,23,24,26,27,29,30,33,34,38
5	26	5,23,26,27,28	1,2,5,6,14,15,11,18,23,24,25,28,32,33,36	3,4,5,6,8,9,11,14,15,17,19,20,22,24,25,26,27,28,29,31,32,33,35,37,38
6	29	9,13,16,27,34	4,8,9,11,12,17,19,20,24,27,29,30,31,35,38	1,2,3,4,5,8,10,13,15,16,18,19,20,21,23,25,26,27,30,31,32,33,35,36,37
7	31	3,8,29,33,34	2,3,4,7,8,11,12,14,15,20,21,27,36,37,38	1,2,6,8,9,10,11,12,16,17,18,19,20,21,22,23,25,27,28,30,31,32,33,36,37
8	33	19,27,30,32,38	2,3,4,8,9,12,13,15,20,23,25,29,30,33,37	1,2,3,5,6,7,8,10,13,14,17,18,20,22,23,25,27,28,30,31,32,34,35,36,38
9	36	14,15,24,34,35	1,2,4,6,7,8,9,12,13,14,17,19,28,31,36	1,3,5,6,9,10,13,14,15,16,17,18,19,21,22,24,25,26,30,31,32,33,34,35,36
10	38	1,7,11,16,21	3,4,15,18,19,21,22,25,26,28,31,33,34,35,37	1,4,6,7,8,9,10,11,12,13,16,17,19,20,21,22,23,24,28,29,30,31,33,34,35

Table A.2: List of candidate well locations for bi-objective models (for Bi-WF and Bi-WNF)

Bi-WF	Bi-WNF	
S^b	$ S_2^b =5$	$ S_2^b =15$
4	6,12,13,26,31	2,3,6,7,8,11,12,13,18,29,30,31,36,37,38
14	5,23,26,27,28	1,2,5,6,14,15,11,18,23,24,25,28,32,33,36
18	$ S_2^b =25$	
29	1,2,3,5,6,7,8,10,12,13,14,16,17,19,20,22,24,25,27,28,29,31,32,35,37	
31	3,4,5,6,8,9,11,14,15,17,19,20,22,24,25,26,27,28,29,31,32,33,35,37,38	

Appendix B

Solution analysis of WF-L and WF-D

Table B.1: Solution analysis of WF-L and WF-D for $\gamma = 60$ and 70

	WF-L							WF-D						
Instance Index	CPU (h)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
					Total	Average	Max						Average	Max
in_60_f1	0:44:11	361.43	8	7	1215.99	32.00	60.00	0:00:20	882.23	572.11	10	5	23.22	45.40
in_60_f2	1:32:47	334.37	9	7	1121.67	29.52	60.00	0:00:21	882.23	555.22	10	5	23.22	45.40
in_60_f3	0:11:16	340.45	10	6	1075.74	28.31	60.00	0:00:16	882.23	572.11	10	6	23.22	45.40
in_60_f4	0:17:35	351.29	10	7	1109.53	29.20	60.00	0:00:26	882.23	579.62	10	7	23.22	45.40
in_60_f5	0:59:22	334.37	8	7	1182.94	31.13	60.00	0:00:18	882.23	565.03	10	7	23.22	45.40
in_60_f6	5:27:19	347.04	8	7	1120.49	29.49	55.07	0:00:29	882.23	568.84	10	4	23.22	45.40
in_60_f7	0:14:40	347.29	8	7	1118.25	29.43	60.00	0:00:42	882.23	589.05	10	9	23.22	45.40
in_60_f8	1:00:18	374.15	8	7	1196.17	31.48	60.00	0:00:26	882.23	602.11	10	10	23.22	45.40
in_60_f9	18:54:16	368.28	8	4	1147.22	30.19	60.00	0:00:30	882.23	572.11	10	9	23.22	45.40
in_60_f10	1:40:14	362.97	9	7	1073.16	28.24	55.07	0:00:44	882.23	601.80	10	6	23.22	45.40
in_70_f1	0:08:17	323.72	7	6	1384.34	36.43	69.97	0:00:12	1012.60	524.87	8	5	26.65	48.84
in_70_f2	0:04:12	276.96	6	4	1482.22	39.01	69.97	0:00:06	1012.60	482.31	8	4	26.65	48.84
in_70_f3	0:01:35	278.45	6	3	1411.33	37.14	69.97	0:00:09	1012.60	486.11	8	4	26.65	48.84
in_70_f4	0:04:01	294.54	6	4	1510.34	39.75	69.97	0:00:05	1012.60	509.13	8	6	26.65	48.84
in_70_f5	0:05:10	293.71	6	5	1419.38	37.35	69.97	0:00:04	1012.60	479.93	8	5	26.65	48.84
in_70_f6	0:04:20	287.71	7	5	1377.78	36.26	69.97	0:00:05	1012.60	473.33	8	4	26.65	48.84
in_70_f7	0:01:20	278.22	6	5	1488.24	39.16	68.48	0:00:05	1012.60	496.87	8	7	26.65	48.84
in_70_f8	0:06:30	329.57	6	5	1469.95	38.68	69.97	0:00:08	1012.60	524.53	8	8	26.65	48.84
in_70_f9	0:09:39	308.18	5	3	1507.22	39.66	69.97	0:00:07	1012.60	479.93	8	4	26.65	48.84
in_70_f10	0:18:47	299.74	6	6	1377.78	36.26	69.97	0:00:10	1012.60	506.28	8	4	26.65	48.84

Table B.2: Solution analysis of WF-L and WF-D for $\gamma = 90$ and 100

	WF-L							WF-D						
Instance Index	CPU (h)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
					Total	Average	Max						Average	Max
in_90_f1	0:00:17	229.92	3	3	1867.86	49.15	87.00	0:00:01	1501.40	336.44	4	2	39.51	81.22
in_90_f2	0:00:12	181.08	4	3	1759.05	46.29	87.00	0:00:01	1501.40	310.26	4	2	39.51	81.22
in_90_f3	0:00:12	190.04	4	3	1924.38	50.64	90.00	0:00:01	1501.40	317.51	4	2	39.51	81.22
in_90_f4	0:00:13	209.90	4	3	1822.51	47.96	87.00	0:00:01	1501.40	324.85	4	3	39.51	81.22
in_90_f5	0:00:18	223.03	4	4	1758.29	46.27	84.48	0:00:01	1501.40	316.12	4	3	39.51	81.22
in_90_f6	0:00:09	186.65	4	2	1760.02	46.32	90.00	0:00:01	1501.40	333.79	4	3	39.51	81.22
in_90_f7	0:00:05	230.08	4	3	1727.20	45.45	90.00	0:00:01	1501.40	360.71	4	4	39.51	81.22
in_90_f8	0:00:19	261.51	4	4	1758.29	46.27	84.48	0:00:01	1501.40	360.71	4	4	39.51	81.22
in_90_f9	0:00:13	214.76	4	2	1760.02	46.32	90.00	0:00:01	1501.40	352.65	4	3	39.51	81.22
in_90_f10	0:00:11	216.65	4	4	1760.02	46.32	90.00	0:00:01	1501.40	346.12	4	4	39.51	81.22
in_100_f1	0:00:05	203.41	3	3	1981.04	52.13	99.05	0:00:01	1792.50	281.36	3	2	47.17	85.38
in_100_f2	0:00:06	174.00	3	3	2146.99	56.50	99.05	0:00:01	1792.50	237.09	3	2	47.17	85.38
in_100_f3	0:00:04	145.99	3	1	2113.11	55.61	99.05	0:00:01	1792.50	247.57	3	2	47.17	85.38
in_100_f4	0:00:06	177.00	3	2	2042.36	53.75	99.36	0:00:01	1792.50	260.17	3	2	47.17	85.38
in_100_f5	0:00:05	198.85	3	3	1965.93	51.74	99.05	0:00:01	1792.50	237.09	3	1	47.17	85.38
in_100_f6	0:00:06	159.55	2	1	2221.78	58.47	99.05	0:00:01	1792.50	244.86	3	2	47.17	85.38
in_100_f7	0:00:05	200.60	2	2	2221.78	58.47	99.05	0:00:01	1792.50	298.65	3	3	47.17	85.38
in_100_f8	0:00:05	237.00	3	3	2042.36	53.75	99.36	0:00:01	1792.50	281.69	3	3	47.17	85.38
in_100_f9	0:00:25	183.09	3	2	2134.69	56.18	99.05	0:00:02	1792.50	255.89	3	2	47.17	85.38
in_100_f10	0:00:05	170.41	3	2	2115.21	55.66	99.05	0:00:01	1792.50	297.09	3	2	47.17	85.38

Appendix C

Solution analysis of WNF-L and WNF-D

Table C.1: Solution analysis of WNF-L and WNF-D for $\gamma = 60$ and 70 ($|S_2|=5$)

	WNF-L								WNF-D						
Instance Index	CPU (h)	Gap (%)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
						Total	Avg	Max						Avg	Max
in_60_nf5_1	2:00:26	65.72	334.37	8	7	1182.94	31.13	60.00	0:01:14	882.23	565.03	10	7	23.22	45.40
in_60_nf5_2	3:17:59	opt	334.37	8	7	1182.94	31.13	60.00	0:00:47	882.23	559.05	10	7	23.22	45.40
in_60_nf5_3	2:00:26	66.82	334.37	8	6	1182.94	31.13	60.00	0:00:21	882.23	559.05	10	7	23.22	45.40
in_60_nf5_4	2:00:23	68.07	340.45	9	7	1105.74	29.10	60.00	0:00:37	882.23	564.29	10	6	23.22	45.40
in_60_nf5_5	2:00:26	73.11	341.06	8	7	1195.93	31.47	60.00	0:00:48	882.23	565.03	10	7	23.22	45.40
in_60_nf5_6	1:02:50	opt	334.37	8	7	1182.94	31.13	60.00	0:00:32	882.23	566.15	10	6	23.22	45.40
in_60_nf5_7	2:00:26	5.33	334.37	8	6	1182.94	31.13	60.00	0:00:24	882.23	557.23	10	4	23.22	45.40
in_60_nf5_8	2:00:27	65.78	334.37	8	7	1182.94	31.13	60.00	0:00:30	882.23	559.05	10	7	23.22	45.40
in_60_nf5_9	2:00:27	6.16	334.37	7	7	1182.94	31.13	60.00	0:00:35	882.23	572.11	10	6	23.22	45.40
in_60_nf5_10	2:00:29	64.22	347.04	8	6	1120.49	29.49	55.07	0:00:31	882.23	555.22	10	5	23.22	45.40
in_70_nf5_1	0:09:11	opt	263.71	6	3	1510.34	39.75	69.97	0:00:07	1012.6	479.93	8	5	26.65	48.84
in_70_nf5_2	2:00:14	27.06	263.71	6	5	1510.34	39.75	69.97	0:00:08	1012.6	473.33	8	4	26.65	48.84
in_70_nf5_3	2:00:27	59.56	263.71	6	5	1510.34	39.75	69.97	0:00:05	1012.6	482.03	8	7	26.65	48.84
in_70_nf5_4	0:15:51	opt	278.45	6	3	1411.33	37.14	69.97	0:00:05	1012.6	479.93	8	7	26.65	48.84
in_70_nf5_5	0:12:40	opt	263.71	6	5	1510.34	39.75	69.97	0:00:08	1012.6	479.93	8	5	26.65	48.84
in_70_nf5_6	2:00:11	21.29	263.71	6	3	1510.34	39.75	69.97	0:00:04	1012.6	479.93	8	6	26.65	48.84
in_70_nf5_7	0:23:08	opt	287.71	7	5	1377.78	36.26	69.97	0:00:05	1012.6	473.33	8	4	26.65	48.84
in_70_nf5_8	2:00:25	48.32	263.71	6	5	1510.34	39.75	69.97	0:00:07	1012.6	479.93	8	6	26.65	48.84
in_70_nf5_9	2:00:26	45.14	264.07	6	4	1510.34	39.75	69.97	0:00:10	1012.6	479.93	8	7	26.65	48.84
in_70_nf5_10	2:00:28	57.52	263.71	6	4	1510.34	39.75	69.97	0:00:04	1012.6	475.82	8	6	26.65	48.84

Table C.2: Solution analysis of WNF-L and WNF-D for $\gamma = 90$ and 100 ($|S_2|=5$)

	WNF-L								WNF-D						
Instance Index	CPU (h)	Gap (%)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
						Total	Avg	Max						Avg	Max
in_90_nf5.1	0:00:45	opt	180.21	4	2	1856.27	48.85	90.00	0:00:01	1501.40	297.85	4	2	39.51	81.22
in_90_nf5.2	0:00:22	opt	186.65	4	2	1760.02	46.32	90.00	0:00:01	1501.40	307.46	4	2	39.51	81.22
in_90_nf5.3	0:00:31	opt	180.21	4	3	1856.27	48.85	90.00	0:00:01	1501.40	303.73	4	2	39.51	81.22
in_90_nf5.4	0:00:37	opt	181.08	3	1	1867.86	49.15	87.00	0:00:01	1501.40	316.12	4	3	39.51	81.22
in_90_nf5.5	0:00:59	opt	200.43	4	2	1760.02	46.32	90.00	0:00:01	1501.40	316.12	4	3	39.51	81.22
in_90_nf5.6	0:00:28	opt	180.88	4	2	1924.38	50.64	90.00	0:00:01	1501.40	303.73	4	2	39.51	81.22
in_90_nf5.7	0:01:20	opt	186.65	4	2	1760.02	46.32	90.00	0:00:01	1501.40	316.12	4	2	39.51	81.22
in_90_nf5.8	0:00:22	opt	186.65	4	2	1760.02	46.32	90.00	0:00:01	1501.40	307.46	4	2	39.51	81.22
in_90_nf5.9	0:00:31	opt	180.21	4	2	1856.27	48.85	90.00	0:00:01	1501.40	310.93	4	2	39.51	81.22
in_90_nf5.10	0:00:32	opt	180.21	4	3	1856.27	48.85	90.00	0:00:01	1501.40	316.12	4	2	39.51	81.22
in_100_nf5.1	0:00:05	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	227.39	3	1	47.17	85.38
in_100_nf5.2	0:00:38	opt	159.55	2	1	2221.78	58.47	99.05	0:00:01	1792.50	234.00	3	3	47.17	85.38
in_100_nf5.3	0:00:04	opt	144.00	3	1	2175.30	57.24	99.05	0:00:01	1792.50	227.39	3	1	47.17	85.38
in_100_nf5.4	0:00:09	opt	145.99	3	1	2113.11	55.61	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf5.5	0:00:12	opt	174.82	2	1	2221.78	58.47	99.05	0:00:01	1792.50	237.09	3	1	47.17	85.38
in_100_nf5.6	0:00:08	opt	144.00	3	1	2146.99	56.50	99.05	0:00:01	1792.50	227.39	3	1	47.17	85.38
in_100_nf5.7	0:00:08	opt	159.55	2	1	2221.78	58.47	99.05	0:00:01	1792.50	244.86	3	2	47.17	85.38
in_100_nf5.8	0:00:07	opt	156.00	2	1	2221.78	58.47	99.05	0:00:01	1792.50	234.00	3	3	47.17	85.38
in_100_nf5.9	0:00:24	opt	145.99	3	1	2099.24	55.24	99.05	0:00:01	1792.50	244.10	3	1	47.17	85.38
in_100_nf5.10	0:00:06	opt	144.00	3	1	2146.99	56.50	99.05	0:00:01	1792.50	237.09	3	2	47.17	85.38

Table C.3: Solution analysis of WNF-L and WNF-D for $\gamma = 60$ and 70 ($|S_2|=15$)

	WNF-L								WNF-D						
Instance Index	CPU (h)	Gap (%)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
						Total	Avg	Max						Avg	Max
in_60_nf15.1	1:05:27	opt	334.37	9	6	1121.67	29.52	60.00	0:00:31	882.23	555.22	10	5	23.22	45.40
in_60_nf15.2	2:00:17	70.89	334.37	7	3	1182.94	31.13	60.00	0:00:42	882.23	558.63	10	4	23.22	45.40
in_60_nf15.3	2:00:28	61.39	334.37	8	5	1182.94	31.13	60.00	0:00:29	882.23	557.23	10	4	23.22	45.40
in_60_nf15.4	0:11:45	opt	334.37	8	7	1182.94	31.13	60.00	0:00:39	882.23	555.22	10	5	23.22	45.40
in_60_nf15.5	2:00:18	66.98	334.37	7	3	1182.94	31.13	60.00	0:00:24	882.23	572.11	10	9	23.22	45.40
in_60_nf15.6	2:00:25	59.29	334.37	8	6	1182.94	31.13	60.00	0:00:33	882.23	559.48	10	7	23.22	45.40
in_60_nf15.7	0:16:15	opt	334.37	8	6	1182.94	31.13	60.00	0:00:29	882.23	555.22	10	5	23.22	45.40
in_60_nf15.8	2:00:28	67.18	347.04	8	7	1120.49	29.49	55.07	0:00:30	882.23	557.23	10	4	23.22	45.40
in_60_nf15.9	2:00:15	68.01	334.37	9	7	1121.67	29.52	60.00	0:00:32	882.23	555.22	10	5	23.22	45.40
in_60_nf15.10	2:00:27	59.58	334.37	8	5	1182.94	31.13	60.00	0:01:15	882.23	559.05	10	7	23.22	45.40
in_70_nf15.1	2:00:26	27.53	263.71	5	3	1543.34	40.61	69.97	0:00:06	1012.60	473.33	8	4	26.65	48.84
in_70_nf15.2	2:00:27	29.17	263.71	5	3	1543.34	40.61	69.97	0:00:11	1012.60	475.82	8	6	26.65	48.84
in_70_nf15.3	2:00:28	33.03	263.71	6	5	1510.34	39.75	69.97	0:00:12	1012.60	475.82	8	6	26.65	48.84
in_70_nf15.4	2:00:28	33.60	263.71	6	3	1510.34	39.75	69.97	0:00:05	1012.60	479.93	8	7	26.65	48.84
in_70_nf15.5	2:00:27	28.16	263.71	6	5	1510.34	39.75	69.97	0:00:04	1012.60	479.93	8	5	26.65	48.84
in_70_nf15.6	2:00:10	45.28	263.71	5	3	1543.34	40.61	69.97	0:00:07	1012.60	473.33	8	4	26.65	48.84
in_70_nf15.7	2:00:28	47.36	263.71	5	3	1543.34	40.61	69.97	0:00:14	1012.60	477.93	8	5	26.65	48.84
in_70_nf15.8	2:00:27	39.97	263.71	5	3	1543.34	40.61	69.97	0:00:11	1012.60	475.43	8	5	26.65	48.84
in_70_nf15.9	2:00:29	31.17	263.71	5	3	1543.34	40.61	69.97	0:00:08	1012.60	479.93	8	7	26.65	48.84
in_70_nf15.10	2:00:28	35.63	263.71	6	4	1510.34	39.75	69.97	0:00:07	1012.60	479.93	8	5	26.65	48.84

Table C.4: Solution analysis of WNF-L and WNF-D for $\gamma = 90$ and 100 ($|S_2|=15$)

	WNF-L								WNF-D						
Instance Index	CPU (h)	Gap (%)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
						Total	Avg	Max						Avg	Max
in_90_nf15_1	0:01:31	opt	180.21	4	2	1856.27	48.85	90.00	0:00:02	1501.40	297.85	4	2	39.51	81.22
in_90_nf15_2	0:01:10	opt	180.21	4	2	1856.27	48.85	90.00	0:00:01	1501.40	297.85	4	2	39.51	81.22
in_90_nf15_3	0:01:34	opt	180.21	4	2	1856.27	48.85	90.00	0:00:02	1501.40	307.46	4	2	39.51	81.22
in_90_nf15_4	0:01:36	opt	180.21	4	3	1856.27	48.85	90.00	0:00:01	1501.40	303.73	4	2	39.51	81.22
in_90_nf15_5	0:01:17	opt	180.21	4	3	1856.27	48.85	90.00	0:00:02	1501.40	310.93	4	2	39.51	81.22
in_90_nf15_6	0:01:13	opt	180.21	4	2	1856.27	48.85	90.00	0:00:01	1501.40	297.85	4	2	39.51	81.22
in_90_nf15_7	0:01:26	opt	180.21	4	3	1856.27	48.85	90.00	0:00:02	1501.40	297.85	4	2	39.51	81.22
in_90_nf15_8	0:00:56	opt	180.21	4	2	1856.27	48.85	90.00	0:00:02	1501.40	297.85	4	2	39.51	81.22
in_90_nf15_9	0:00:31	opt	180.21	4	2	1856.27	48.85	90.00	0:00:02	1501.40	297.85	4	2	39.51	81.22
in_90_nf15_10	0:01:17	opt	180.21	4	3	1856.27	48.85	90.00	0:00:02	1501.40	307.46	4	2	39.51	81.22
in_100_nf15_1	0:00:34	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	227.39	3	2	47.17	85.38
in_100_nf15_2	0:00:16	opt	144.00	3	2	2175.30	57.24	99.05	0:00:01	1792.50	227.39	3	2	47.17	85.38
in_100_nf15_3	0:00:21	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf15_4	0:00:18	opt	144.00	3	1	2175.30	57.24	99.05	0:00:01	1792.50	227.39	3	1	47.17	85.38
in_100_nf15_5	0:00:41	opt	145.99	3	1	2099.24	55.24	99.05	0:00:01	1792.50	244.10	3	1	47.17	85.38
in_100_nf15_6	0:00:33	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf15_7	0:00:25	opt	144.00	3	2	2175.30	57.24	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf15_8	0:00:24	opt	144.00	3	1	2175.30	57.24	99.05	0:00:01	1792.50	227.39	3	1	47.17	85.38
in_100_nf15_9	0:00:13	opt	144.00	3	2	2175.30	57.24	99.05	0:00:01	1792.50	227.39	3	1	47.17	85.38
in_100_nf15_10	0:00:28	opt	145.99	3	1	2099.24	55.24	99.05	0:00:01	1792.50	234.00	3	1	47.17	85.38

Table C.5: Solution analysis of WNF-L and WNF-D for $\gamma = 60$ and 70 ($|S_2|=25$)

	WNF-L								WNF-D						
Instance Index	CPU (h)	Gap (%)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
						Total	Avg	Max						Avg	Max
in_60_nf25.1	2:00:29	63.89	334.37	9	6	1121.67	29.52	60.00	0:00:29	882.23	557.23	10	4	23.22	45.40
in_60_nf25.2	2:00:24	62.11	347.04	8	6	1120.49	29.49	55.07	0:00:19	882.23	562.38	10	7	23.22	45.40
in_60_nf25.3	2:00:28	59.60	334.37	8	6	1182.94	31.13	60.00	0:00:26	882.23	555.22	10	5	23.22	45.40
in_60_nf25.4	0:25:47	opt	334.37	8	7	1182.94	31.13	60.00	0:00:14	882.23	555.22	10	5	23.22	45.40
in_60_nf25.5	2:00:15	67.43	334.37	8	6	1182.94	31.13	60.00	0:00:14	882.23	558.63	10	4	23.22	45.40
in_60_nf25.6	2:00:13	65.47	334.37	8	6	1182.94	31.13	60.00	0:00:23	882.23	557.23	10	4	23.22	45.40
in_60_nf25.7	2:00:29	70.59	347.38	9	7	1159.68	30.52	60.00	0:00:33	882.23	559.05	10	7	23.22	45.40
in_60_nf25.8	0:16:39	opt	334.37	9	8	1121.67	29.52	60.00	0:00:28	882.23	555.22	10	5	23.22	45.40
in_60_nf25.9	2:00:27	68.59	334.37	8	6	1182.94	31.13	60.00	0:00:18	882.23	559.05	10	7	23.22	45.40
in_60_nf25.10	2:00:18	69.00	347.38	9	7	1159.68	30.52	60.00	0:00:25	882.23	555.22	10	5	23.22	45.40
in_70_nf25.1	2:00:12	52.84	263.71	6	3	1510.34	39.75	69.97	0:00:10	1012.6	473.33	8	4	26.65	48.84
in_70_nf25.2	2:00:27	40.88	263.71	6	4	1510.34	39.75	69.97	0:00:15	1012.6	473.33	8	4	26.65	48.84
in_70_nf25.3	2:00:28	34.76	263.71	5	3	1543.34	40.61	69.97	0:00:12	1012.6	473.33	8	4	26.65	48.84
in_70_nf25.4	0:06:54	opt	263.71	6	5	1510.34	39.75	69.97	0:00:07	1012.6	473.33	8	4	26.65	48.84
in_70_nf25.5	0:06:00	opt	263.71	6	5	1510.34	39.75	69.97	0:00:09	1012.6	473.33	8	4	26.65	48.84
in_70_nf25.6	2:00:27	47.23	263.71	6	4	1510.34	39.75	69.97	0:00:11	1012.6	475.82	8	5	26.65	48.84
in_70_nf25.7	2:00:11	52.05	263.71	5	3	1543.34	40.61	69.97	0:00:06	1012.6	475.82	8	5	26.65	48.84
in_70_nf25.8	2:00:28	48.61	263.71	6	5	1510.34	39.75	69.97	0:00:10	1012.6	482.03	8	7	26.65	48.84
in_70_nf25.9	2:00:12	58.70	263.71	6	5	1510.34	39.75	69.97	0:00:10	1012.6	475.82	8	5	26.65	48.84
in_70_nf25.10	0:05:51	opt	263.71	6	5	1510.34	39.75	69.97	0:00:07	1012.6	473.33	8	5	26.65	48.84

Table C.6: Solution analysis of WNF-L and WNF-D for $\gamma = 90$ and 100 ($|S_2|=25$)

	WNF-L								WNF-D						
Instance Index	CPU (h)	Gap (%)	Objective of WF-L	# of WDU	Max Flow	Meters Walked			CPU (h)	Objective of WF-D	Network Length	# of WDU	Max Flow	Meters Walked	
						Total	Avg	Max						Avg	Max
in_90_nf25_1	0:02:10	opt	180.21	4	3	1856.27	48.85	90.00	0:00:03	1501,4	297,85	4	2	39.51	81.22
in_90_nf25_2	0:01:34	opt	180.21	4	3	1856.27	48.85	90.00	0:00:03	1501,4	303,73	4	2	39.51	81.22
in_90_nf25_3	0:01:50	opt	180.21	4	3	1856.27	48.85	90.00	0:00:02	1501,4	297,85	4	2	39.51	81.22
in_90_nf25_4	0:01:40	opt	180.21	4	3	1856.27	48.85	90.00	0:00:03	1501,4	297,85	4	2	39.51	81.22
in_90_nf25_5	0:01:11	opt	180.21	4	2	1856.27	48.85	90.00	0:00:02	1501,4	307,46	4	2	39.51	81.22
in_90_nf25_6	0:00:35	opt	180.21	4	2	1856.27	48.85	90.00	0:00:04	1501,4	303,73	4	2	39.51	81.22
in_90_nf25_7	0:01:30	opt	180.21	4	2	1856.27	48.85	90.00	0:00:03	1501,4	297,85	4	2	39.51	81.22
in_90_nf25_8	0:01:16	opt	180.21	4	3	1856.27	48.85	90.00	0:00:04	1501,4	303,73	4	2	39.51	81.22
in_90_nf25_9	0:02:04	opt	180.21	4	2	1856.27	48.85	90.00	0:00:02	1501,4	303,73	4	2	39.51	81.22
in_90_nf25_10	0:01:26	opt	180.21	4	2	1856.27	48.85	90.00	0:00:05	1501,4	297,85	4	2	39.51	81.22
in_100_nf25_1	0:00:13	opt	144.00	3	2	2175.30	57.24	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf25_2	0:00:41	opt	144.00	3	2	2175.30	57.24	99.05	0:00:01	1792.50	227.39	3	2	47.17	85.38
in_100_nf25_3	0:00:29	opt	144.00	3	2	2146.99	56.50	99.05	0:00:02	1792.50	223.51	3	1	47.17	85.38
in_100_nf25_4	0:00:35	opt	144.00	3	2	2175.30	57.24	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf25_5	0:00:21	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf25_6	0:00:37	opt	144.00	3	2	2175.30	57.24	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf25_7	0:00:57	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf25_8	0:00:43	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	223.51	3	1	47.17	85.38
in_100_nf25_9	0:00:24	opt	144.00	3	2	2146.99	56.50	99.05	0:00:01	1792.50	227.39	3	2	47.17	85.38
in_100_nf25_10	0:00:32	opt	144.00	3	2	2175.30	57.24	99.05	0:00:02	1792.50	223.51	3	1	47.17	85.38

Appendix D

Number of Nodes Walking Under Certain Threshold

Table D.1: Number of nodes walking under certain threshold, for $\gamma = 60, 70$ and 80, well is fixed

Instance Index	WF-L			WF-D		
	# of nodes walking ≤ 20	≤ 40	≤ 60	# of nodes walking ≤ 20	≤ 40	≤ 60
in_60_f1	8	24	38	13	35	38
in_60_f2	9	27	38	13	35	38
in_60_f3	11	26	38	13	35	38
in_60_f4	11	27	38	13	35	38
in_60_f5	8	25	38	13	35	38
in_60_f6	9	26	38	13	35	38
in_60_f7	9	26	38	13	35	38
in_60_f8	8	25	38	13	35	38
in_60_f9	9	25	38	13	35	38
in_60_f10	10	26	38	13	35	38
in_70_f1	7	21	34	11	31	38
in_70_f2	6	18	33	11	31	38
in_70_f3	7	19	33	11	31	38
in_70_f4	6	17	32	11	31	38
in_70_f5	6	19	34	11	31	38
in_70_f6	7	20	33	11	31	38
in_70_f7	6	16	33	11	31	38
in_70_f8	6	18	33	11	31	38
in_70_f9	5	17	33	11	31	38
in_70_f10	7	20	33	11	31	38
in_80_f1	6	18	29	8	24	38
in_80_f2	5	16	31	8	24	38
in_80_f3	7	17	30	8	24	38
in_80_f4	6	18	29	8	24	38
in_80_f5	6	21	31	8	24	38
in_80_f6	6	18	30	8	24	38
in_80_f7	5	14	30	8	24	38
in_80_f8	6	19	29	8	24	38
in_80_f9	7	19	31	8	24	38
in_80_f10	5	13	27	8	24	38

Table D.2: Number of nodes walking under certain threshold for $\gamma = 90$ and 100, well is fixed

Instance Index	WF-L			WF-D		
	# of nodes walking			# of nodes walking		
	≤ 20	≤ 40	≤ 60	≤ 20	≤ 40	≤ 60
in_90_f1	3	13	25	5	18	34
in_90_f2	4	15	27	5	18	34
in_90_f3	4	13	23	5	18	34
in_90_f4	4	13	25	5	18	34
in_90_f5	4	14	26	5	18	34
in_90_f6	4	16	28	5	18	34
in_90_f7	4	15	29	5	18	34
in_90_f8	4	14	26	5	18	34
in_90_f9	4	16	28	5	18	34
in_90_f10	4	16	28	5	18	34
in_100_f1	3	12	24	3	14	26
in_100_f2	3	12	21	3	14	26
in_100_f3	4	11	21	3	14	26
in_100_f4	3	11	23	3	14	26
in_100_f5	3	11	23	3	14	26
in_100_f6	2	9	19	3	14	26
in_100_f7	2	9	19	3	14	26
in_100_f8	3	11	23	3	14	26
in_100_f9	3	10	21	3	14	26
in_100_f10	3	11	21	3	14	26

Table D.3: Number of nodes walking under certain threshold for $\gamma = 60, 70$ and 80 ($|S_2|=5$)

Instance Index	WNF-L			WNF-D		
	# of nodes walking			# of nodes walking		
	≤ 20	≤ 40	≤ 60	≤ 20	≤ 40	≤ 60
in_60_nf5_1	8	25	38	8	24	38
in_60_nf5_2	8	25	38	8	24	38
in_60_nf5_3	8	25	38	8	24	38
in_60_nf5_4	10	26	38	8	24	38
in_60_nf5_5	8	24	38	8	24	38
in_60_nf5_6	8	25	38	8	24	38
in_60_nf5_7	8	25	38	8	24	38
in_60_nf5_8	8	25	38	8	24	38
in_60_nf5_9	8	25	38	8	24	38
in_60_nf5_10	9	26	38	8	24	38
in_70_nf5_1	6	17	32	5	18	34
in_70_nf5_2	6	17	32	5	18	34
in_70_nf5_3	6	17	32	5	18	34
in_70_nf5_4	7	19	33	5	18	34
in_70_nf5_5	6	17	32	5	18	34
in_70_nf5_6	6	17	32	5	18	34
in_70_nf5_7	7	20	33	5	18	34
in_70_nf5_8	6	17	32	5	18	34
in_70_nf5_9	6	17	32	5	18	34
in_70_nf5_10	6	17	32	5	18	34
in_80_nf5_1	6	18	29	8	24	38
in_80_nf5_2	6	18	29	8	24	38
in_80_nf5_3	6	18	29	8	24	38
in_80_nf5_4	6	18	29	8	24	38
in_80_nf5_5	6	18	29	8	24	38
in_80_nf5_6	6	18	29	8	24	38
in_80_nf5_7	5	13	27	8	24	38
in_80_nf5_8	6	18	29	8	24	38
in_80_nf5_9	6	18	29	8	24	38
in_80_nf5_10	6	18	29	8	24	38

Table D.4: Number of nodes walking under certain threshold for $\gamma = 90$ and 100 ($|S_2|=5$)

Instance Index	WNF-L			WNF-D		
	# of nodes walking ≤ 20	≤ 40	≤ 60	# of nodes walking ≤ 20	≤ 40	≤ 60
in_90_nf5_1	4	14	24	5	18	34
in_90_nf5_2	4	16	28	5	18	34
in_90_nf5_3	4	14	24	5	18	34
in_90_nf5_4	3	13	25	5	18	34
in_90_nf5_5	4	16	28	5	18	34
in_90_nf5_6	4	13	23	5	18	34
in_90_nf5_7	4	16	28	5	18	34
in_90_nf5_8	4	16	28	5	18	34
in_90_nf5_9	4	14	24	5	18	34
in_90_nf5_10	4	14	24	5	18	34
in_100_nf5_1	3	12	21	3	14	26
in_100_nf5_2	2	9	19	3	14	26
in_100_nf5_3	3	10	21	3	14	26
in_100_nf5_4	4	11	21	3	14	26
in_100_nf5_5	2	9	19	3	14	26
in_100_nf5_6	3	12	21	3	14	26
in_100_nf5_7	2	9	19	3	14	26
in_100_nf5_8	2	9	19	3	14	26
in_100_nf5_9	3	10	22	3	14	26
in_100_nf5_10	3	12	21	3	14	26

Table D.5: Number of nodes walking under certain threshold for $\gamma = 60, 70$ and 80 ($|S_2|=15$)

Instance Index	WNF-L			WNF-D		
	# of nodes walking			# of nodes walking		
	≤ 20	≤ 40	≤ 60	≤ 20	≤ 40	≤ 60
in_60_nf15_1	9	27	38	13	35	38
in_60_nf15_2	8	25	38	13	35	38
in_60_nf15_3	8	25	38	13	35	38
in_60_nf15_4	8	25	38	13	35	38
in_60_nf15_5	8	25	38	13	35	38
in_60_nf15_6	8	25	38	13	35	38
in_60_nf15_7	8	25	38	13	35	38
in_60_nf15_8	9	26	38	13	35	38
in_60_nf15_9	9	27	38	13	35	38
in_60_nf15_10	8	25	38	13	35	38
in_70_nf15_1	5	17	32	11	31	38
in_70_nf15_2	5	17	32	11	31	38
in_70_nf15_3	6	17	32	11	31	38
in_70_nf15_4	6	17	32	11	31	38
in_70_nf15_5	6	17	32	11	31	38
in_70_nf15_6	5	17	32	11	31	38
in_70_nf15_7	5	17	32	11	31	38
in_70_nf15_8	5	17	32	11	31	38
in_70_nf15_9	5	17	32	11	31	38
in_70_nf15_10	6	17	32	11	31	38
in_80_nf15_1	6	18	29	8	24	38
in_80_nf15_2	6	18	29	8	24	38
in_80_nf15_3	6	18	29	8	24	38
in_80_nf15_4	6	18	29	8	24	38
in_80_nf15_5	6	18	29	8	24	38
in_80_nf15_6	6	18	29	8	24	38
in_80_nf15_7	6	18	29	8	24	38
in_80_nf15_8	6	18	29	8	24	38
in_80_nf15_9	6	18	29	8	24	38
in_80_nf15_10	6	18	29	8	24	38

Table D.6: Number of nodes walking under certain threshold for $\gamma = 90$ and 100 ($|S_2|=15$)

Instance Index	WNF-L			WNF-D		
	# of nodes walking ≤ 20	≤ 40	≤ 60	# of nodes walking ≤ 20	≤ 40	≤ 60
in_90_nf15_1	4	14	24	5	18	34
in_90_nf15_2	4	14	24	5	18	34
in_90_nf15_3	4	14	24	5	18	34
in_90_nf15_4	4	14	24	5	18	34
in_90_nf15_5	4	14	24	5	18	34
in_90_nf15_6	4	14	24	5	18	34
in_90_nf15_7	4	14	24	5	18	34
in_90_nf15_8	4	14	24	5	18	34
in_90_nf15_9	4	14	24	5	18	34
in_90_nf15_10	4	14	24	5	18	34
in_100_nf15_1	3	12	21	3	14	26
in_100_nf15_2	3	10	21	3	14	26
in_100_nf15_3	3	12	21	3	14	26
in_100_nf15_4	3	10	21	3	14	26
in_100_nf15_5	3	10	22	3	14	26
in_100_nf15_6	3	12	21	3	14	26
in_100_nf15_7	3	10	21	3	14	26
in_100_nf15_8	3	10	21	3	14	26
in_100_nf15_9	3	10	21	3	14	26
in_100_nf15_10	3	10	22	3	14	26

Table D.7: Number of nodes walking under certain threshold for $\gamma = 60, 70$ and 80 ($|S_2|=25$)

Instance Index	WNF-L			WNF-D		
	# of nodes walking			# of nodes walking		
	≤ 20	≤ 40	≤ 60	≤ 20	≤ 40	≤ 60
in_60_nf25_1	9	27	38	13	35	38
in_60_nf25_2	9	26	38	13	35	38
in_60_nf25_3	8	25	38	13	35	38
in_60_nf25_4	8	25	38	13	35	38
in_60_nf25_5	8	25	38	13	35	38
in_60_nf25_6	8	25	38	13	35	38
in_60_nf25_7	8	25	38	13	35	38
in_60_nf25_8	9	27	38	13	35	38
in_60_nf25_9	8	25	38	13	35	38
in_60_nf25_10	8	25	38	13	35	38
in_70_nf25_1	6	17	32	11	31	38
in_70_nf25_2	6	17	32	11	31	38
in_70_nf25_3	5	17	32	11	31	38
in_70_nf25_4	6	17	32	11	31	38
in_70_nf25_5	6	17	32	11	31	38
in_70_nf25_6	6	17	32	11	31	38
in_70_nf25_7	5	17	32	11	31	38
in_70_nf25_8	6	17	32	11	31	38
in_70_nf25_9	6	17	32	11	31	38
in_70_nf25_10	6	17	32	11	31	38
in_80_nf25_1	6	18	29	8	24	38
in_80_nf25_2	6	18	29	8	24	38
in_80_nf25_3	6	18	29	8	24	38
in_80_nf25_4	6	18	29	8	24	38
in_80_nf25_5	6	18	29	8	24	38
in_80_nf25_6	6	18	29	8	24	38
in_80_nf25_7	6	18	29	8	24	38
in_80_nf25_8	6	18	29	8	24	38
in_80_nf25_9	6	18	29	8	24	38
in_80_nf25_10	6	18	29	8	24	38

Table D.8: Number of nodes walking under certain threshold for $\gamma = 90$ and 100 ($|S_2|=25$)

Instance Index	WNF-L			WNF-D		
	# of nodes walking ≤ 20	≤ 40	≤ 60	# of nodes walking ≤ 20	≤ 40	≤ 60
in_90_nf25_1	4	14	24	5	18	34
in_90_nf25_2	4	14	24	5	18	34
in_90_nf25_3	4	14	24	5	18	34
in_90_nf25_4	4	14	24	5	18	34
in_90_nf25_5	4	14	24	5	18	34
in_90_nf25_6	4	14	24	5	18	34
in_90_nf25_7	4	14	24	5	18	34
in_90_nf25_8	4	14	24	5	18	34
in_90_nf25_9	4	14	24	5	18	34
in_90_nf25_10	4	14	24	5	18	34
in_100_nf25_1	3	10	21	3	14	26
in_100_nf25_2	3	10	21	3	14	26
in_100_nf25_3	3	12	21	3	14	26
in_100_nf25_4	3	10	21	3	14	26
in_100_nf25_5	3	12	21	3	14	26
in_100_nf25_6	3	10	21	3	14	26
in_100_nf25_7	3	12	21	3	14	26
in_100_nf25_8	3	12	21	3	14	26
in_100_nf25_9	3	12	21	3	14	26
in_100_nf25_10	3	10	21	3	14	26