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Optimization Models for Network Design of a District Cooling System

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Declaration

To the best of my knowledge, this thesis contains no material previously published or written by another person or institution, except where due reference is made in the text of the thesis. This thesis contains no material which has been accepted for the award of any other degree in any university or other institution.

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Committee

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We, the committee members listed below, accept and approve the Thesis/Dissertation of the student named above. To the best of this committees knowledge, the Thesis/Dissertation conforms the requirements of Qatar University, and we endorse this Thesis for examination.

Supervisor Prof. Mohamed Haouari

Signature ______________________________ Date __________

Abstract

As the ecological dimension is becoming increasingly important in today's carbonized globe, solutions that are energy efficient and environmentally conscious are highly encouraged in almost every field. Noticeably, international and regional initiatives have stressed the urgency in adapting new cooling solutions to conform to the stricter environmental standards while meeting the current rising demand of cooling services. Pertinently, District Cooling System (DCS) stands as a greener alternative for the commonly used air conditioning systems. From a holistic standpoint, paying premium attention on such sustainable initiative is not fully merited if it is not coupled with economic enhancement. Even though DCS is found to be operationally efficient, the capital cost of building and installing its infrastructure is relatively high and may hinder its rapid adoption. In this dissertation, optimization models are developed and tested for the design of a DC network. The objective is to find an optimal structure of a DCS so that the total investment and operational costs are minimized. This involves optimizing decisions related to chiller plant capacity, storage tank capacity, piping network size and layout, and quantities to be produced and stored during every period of time. A tree-like network is assumed to connect a centralized cooling source with a set of customer's premises. The produced cooling effect, being chilled water, in addition to the stored one (if any) shall be enough to satisfy the aggregate known demand of all customers at every period of time. Essentially, main distribution pipelines shall be installed and connected in such a way that ensures the timely delivery of cooling effect to each customer, in the desired thermal condition (as contracted), and at the lowest cost. Towards this end, Mixed-Integer Linear Programming (MILP) models that explicitly capture the unique characteristics of a DCS are developed. The proposed models capture and accommodate constraints related to both structural and technical aspects. More specifically, models were built to include both thermal and hydraulic characteristics of the system. Reformulation Linearization Technique (RLT) was used to convert a nonlinear problem formulation of the network design problem into an equivalent linear one. Computational experiments, carried out on networks with up to 60 nodes, demonstrate that both optimal and near-optimal solutions can be provided with a reasonable computing time.

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Dedication

To who lives within and beyond myself, to you $\sim$ family, friends and beloved ones.

Acronyms

DCS District Cooling System

DES District Energy System

DHCS District Heating and Cooling System

DHS District Heating System

ETS Energy Transfer Station

MILP Mixed-integer Linear Programming

MINLP Mixed-integer Non-linear Programming

MIP Mixed-integer Programming

ND Network Design

PDO Plant Design and Operations

RLT Reformulation Linearization Technique

TES Thermal Energy Storage

Chapter 1

Introduction

Driven by the anticipated increase in energy demand and knitted together with a rapid rise in CO_2 emission levels, the notion of "sustainable systems" has gained an ever growing attention in current universal, regional and national plans. One example of such systems is District Cooling System (DCS). The main function of a DCS is to mass-produce cooling requirements of a group of buildings while ensuring a tailored provision to each of them, depending on their needs. Hence, DCS appears as an alternative for the power-driven air conditioning systems being operated at individual buildings. Worldwide, the current status quo of energy usage shows that at least 10% of electricity is used for cooling purposes [1]. This percentage is even much higher in some hot climatic countries such as Gulf Cooperation Council (GCC) countries, where air conditioning accounts for 50% of its annual electricity consumption [2]. For this reason, DCS are recently gaining a remarkable market position across the globe as they can reduce electricity consumption by 25% to 40% when compared to conventional air conditioning systems [3].

This chapter introduces the reader to system's components, its benefits, applications and significance. It also highlights the scope of this dissertation while giving a brief summary on the report organization

1.1 Overview of DCSs

District cooling refers to the process of providing space and/or process cooling services to several customers. These customers can be of diverse nature, being service facilities such as commercial centers, airports, hospitals, warehouses, dwellings and schools or industrial facilities such as factories and production plants. In general terms, district cooling system is composed of production system, distribution system and consumption system (represented in customer's premises). Figure 1.1 below illustrates a conceptual system model for a typical district cooling system.

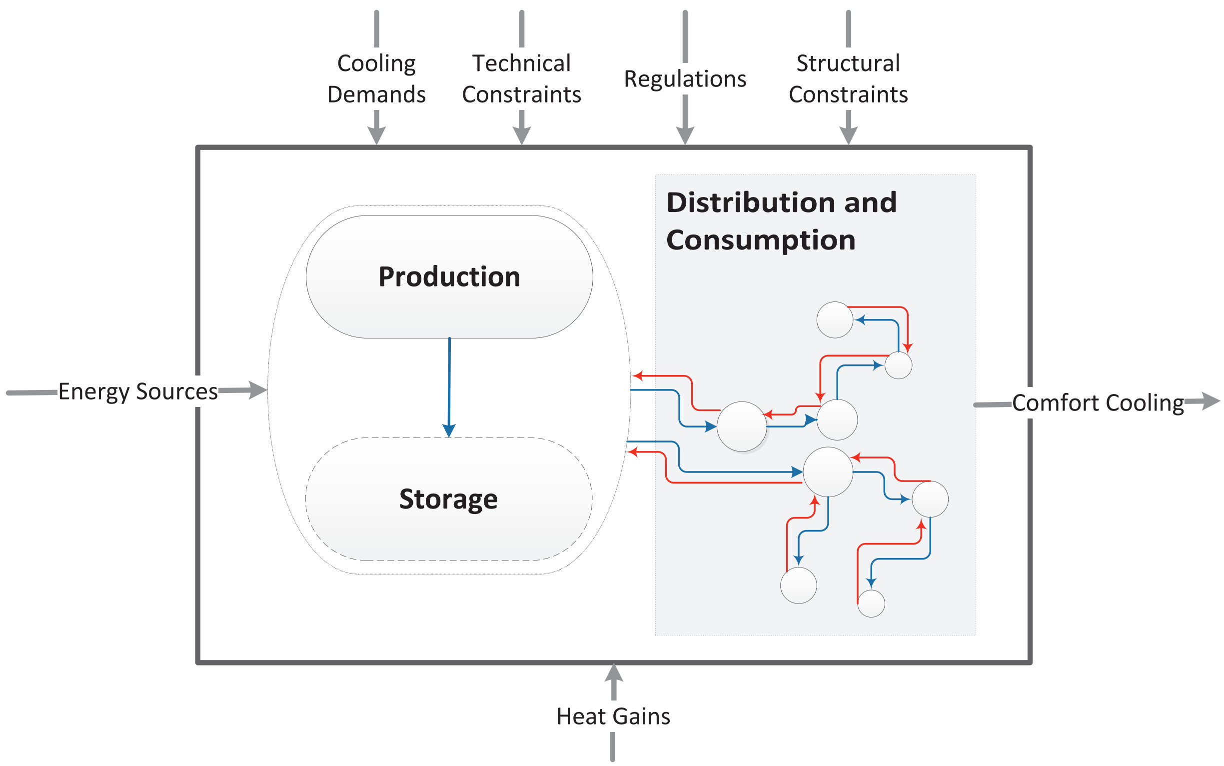

Figure 1.1: System View of District Cooling Technology

As represented, district cooling system can be viewed in terms of six key elements; they are:

- **Inputs:** presented in the energy sources (conventional or renewable) which are responsible for driving the production of chilled water. It also includes the unwanted inputs such as heat gains that can possibly enter the system during both the production and/or distribution process.

- **Outputs:** presented in cooled air in case of space cooling, that ultimately generate the comfort cooling value of operating the system.

- **Processes:** summarized in two main processes which are the production, and distribution; and one non compulsory process; namely, the storage.

- **Constraints/Control:** These are direct factors that control the design and operation of the system. This includes structural related constraints (such as governmental regulation and available corridors for pipelines installation), technical constraints that are necessary for the system to function (mainly the hydraulics of the system) and constraints that governs the ability of the system to meet the service requirements (in right amounts at right temperature levels).

- **Boundaries:** presented in the district borders in which the cooling services are not provided beyond.

- **Environment:** corresponds to any entity outside the boundaries that has no impact on the system. In this case, it is presented in surrounding elements such as customers outside the district.

In view to this, a DCS can be defined as an interconnected system encompassing a centralized chiller plant, main distribution network and clusters of consumer's buildings. A general structure of a DCS is illustrated in Figure 1.2 below. In this figure, the blue and red links refer to the flow of chilled water, and return warm water, respectively.

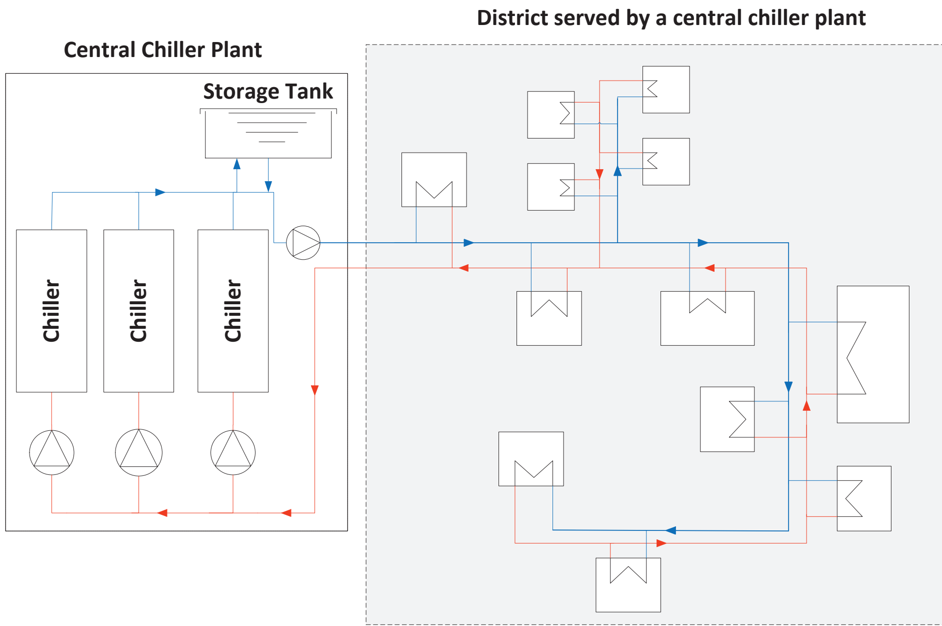

Figure 1.2: Example of a DCS configuration

The cooling effect, in form of chilled water, is produced in the plant and then distributed to individual customers through a distribution network. This distribution network constitutes of two-pipe system, in which the chilled water is transported through supply pipe to the customer; and then recirculated back to the cooling plant through a separate return pipe to be reused, forming a closed loop system [4]. In more advanced settings, DCS is complemented with a Thermal Energy Storage (TES) that is configured with the chiller plant. This optional installation increases systems overall flexibility as the cooling requirements are not required to be met by chiller plant at all point of times; rather, excess cooling effect can be produced during non-peak hours and stored for future use, especially during peak hours [5].

1.2 Benefits of DCSs

The growing importance placed on district cooling is explained by the system's capability in accelerating the pace of economic and environmental advancement without altering the service requirement. In here, the focus will be on identifying the resulted benefits from using such system; yet, system's characteristics that enable these benefits are to be discussed henceforth in Chapter 2.

Prominently, this technology is considered as one of the efficient ways to reduce greenhouse gas emissions (GHG), including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions; hence, supporting green ecosystem practices [5]. DCSs consume less energy; hence, provide improved operational efficiency when comparing them with conventional cooling systems [6]. To put it in numbers, DCSs are capable of reducing electricity consumption by 25% to 40% when compared to conventional air conditioning systems [3]. Additionally, consumers who are getting their cooling demand satisfied from district cooling system enjoys floor space saving as there is no need to keep any cooling equipment in premises like when using traditional cooling systems. Table 1.1 below illustrates these benefits from customer and nation perspectives by mapping them into three categories, namely, environment, economic and performance [7].

1.3 Global and Regional Applications of DCSs

District cooling technology gained a remarkable market position across the universe. They are adopted in the United States, Japan, Korea and many Western and Eastern European countries such as Austria, Finland, France, Germany, Italy, Norway, Slovenia, and Sweden [8]. Generally, the market of DC has not matured enough as it emerged quite recently; yet, its adoption

Table 1.1: Benefits of DCSs

	End Users	Community
Environment	• Reduced noise in buildings. • More architectural freedom due to floor space saving. • Avoiding use of cooling chemicals at the premises.	• Support global initiatives in reducing GHG emissions. • Reduced CO_2 emission per Capita. • Reduced energy consumption per capita. • Improved buildings aesthetics/design.
Economic	• Less expensive when compared to other alternatives. • Reduced capital cost. • Clear cost profile with no hidden costs.	• Allow tapping into the economies of scale when mass-produce the cooling effect.
Performance	• Enhanced reliability. • No in-house maintenance needed.	• Higher energy utilization. • Reduced energy consumption.

trend is on the rise. For instance, a tenfold growth in its installed capacity was observed in Europe during the last decade [1]. Nonetheless, DCSs are recently gaining ground in the Middle East, particularly in the GCC countries due to their desert climate. For example, it was observed that 14% of GCC cooling demand was satisfied by means of DCSs in 2010 [9]. The result of surveying existing applications of DC in different part of the world is summarized in what follows.

In Asia, Japan has the lion share in district cooling system installations. Given Japan climate which varies dramatically from north to south, these systems are found in joint with district heating systems forming what is known as District Heating and Cooling (DHC) systems [10]. Alongside, the Korean government has posed similar attitude in its application of DHC system with 22 DHC plants serving over 940 000 customers (90% are residential users) in 2007 [11]. Additionally, district cooling plants are established in Singapore, Malaysia and China.

In the United States, hundreds of large scale district heating and cooling facilities are currently in operation. Pertinently, two key market segments house these systems: downtown district energy systems (72 systems serving 1,888 million square feet of building space with over 1 million tons of cooling capacity), and university campus district energy systems (330 systems serving 2,487 million square feet of building space with almost 2 million tons of cooling capacity) [12].

In Europe, key urban centers such as Amsterdam, Paris, Vienna, Barcelona, Stockholm, Helsinki, and Gothenburg have these systems in operation and more are currently under construction or in the planning phase to meet the European 2020 vision [13]. To put it in numbers, there are around 100 DCSs operationalized in high dense European city centers and commercial areas especially in France, Sweden, Germany and Italy [14].

In the Middle East [9], the market of district cooling is expected to grow at a compound annual growth rate of 15.4% from 2010 to 2016 with expected revenue of 2.63 billion US Dollars in 2016. In particular, Gulf Cooperation Council (GCC) countries stand as a fertile market for such system. In 2010, district cooling systems were operating with a capacity of 4.8 million tons of refrigeration while the total cooling demand was around 33 million tons of refrigeration in GCC region. By this, penetration rate of district cooling was found to be around 14 percent. United Arab Emirates (UAE) took the lead with 48 percent share of the total district cooling market in that year. In 2012, UAE generated more than 40 percent of the total revenue of GCC district cooling market.

1.4 Practical Significance of DCSs for Qatar

For the case of cold regions such as Canada, the benefits achieved through district heating systems are much higher than the ones obtained from DCSs [15]. This is evidently clear as the energy demand for space heating is higher than that for space cooling in such countries. On the contrary, the desert climate prevailing countries located in the Arabian Peninsula mandate continuous supply of cooling services, resulting in greater need for DCSs. Certainly, Qatar demand for cooling services is massive not only due to the climatic conditions resulted from its location over the Persian Gulf, but also because of the economic boom it is currently facing. The host of mega events such as FIFA 2022 is one of Qatar's internationalization practices that lead to rapid development in real estate market, expansion of existing infrastructure, and the establishment of new cities to cater for the increase in population and number of visitors; all together has contributed to the increasing demand of space cooling supply and services. Features characterizing Qatar such as high CO_2 emissions per capita, high energy consumption, and high-density building clusters makes DCS an attractive cooling option in which both its economic and environmental benefits can be realized.

Given their environmental benefits, District Cooling Systems present an opportunity that supports Qatar's goal of lowering carbon dioxide emissions, thus reducing the country's share in global climate change. Beside the fact that Qatar has experienced a reduction in CO_2 emission per capita in the past ten years (due to population growth), Qatar carbon footprint is still higher than that experienced in all leading industrial and developed countries. Based on statistics published by the International Energy Agency (IEA), Qatar remained featuring the world's highest per capita emissions in 2013 with 38.17 tons of CO_2 per capita [16]. Even though energy production activities hold the lion's share of carbon dioxide emissions, consumption activities have noticeable contribution in these values. Households and commercial users account for 33% of total carbon emissions, in which 18% are resulted from both electricity and water consumption in domestic and commercial buildings [17]. As electricity use is one form of indirect CO_2 emissions that contribute to the overall GHG emissions, having a cooling system in place that utilize sources other than electricity is of a vital importance. In Qatar, it was found that electricity consumption is 16.10 MWh per capita in 2013; which is five times higher than the Middle East consumption (3.53 MWh per capita) [16]. The free pricing of electricity for citizen's domestic use, the extremely hot weather and the high humidity level coupled with the drastic reliance on decentralized air-conditioning devices that unavoidably electrically driven, are key reasons that push the electricity usage in Qatar to an extreme end [18]. According to Qatar National Development Strategy 2011-2016, the wider use of DCSs on domestic and commercial premises would save on power and further, results in the environmental benefit [17]. This is technically true as DCS can operate with technologies that support the use of different energy sources such as steam, hot water from a solar array or waste heat (mainly when using the absorption type). Therefore, utilizing technologies and settings such these found in DCS will reduce electricity usage and will eventually lead to less CO_2 emission; thereby, less contribution to the global climate changes.

DCS are not only environment friendly; they are economically worthy as well. While less clear economic advantages are realized from operating thermal networks in low density residential areas, having them in densely populated urban areas is found to be more financially beneficial [19]. According to Chan et al. (2007), District Cooling System provides both economic and environmental benefits where the cooling load density is high [20]. Meanwhile, the increased population in Qatar is concentrated in Doha, the capital of Qatar;

making DCS an attractive cooling alternative over conventional cooling technologies. It was reported that population density in Doha is about 3136 persons per squared kilometers, while it does not exceed 8 persons per squared kilometers in Al-Shamal municipality [21]. This observed imbalance in geographical distribution of population results in having high-density building clusters including dwellings, shopping malls, and institutional buildings in one area, which presents an opportunity for exploiting both the environmental and economic advantages of DCSs.

1.5 Scope of the Study

Beyond acknowledging the complexity of such thermal application, this study recognizes the importance of optimally designing DC distribution networks. Even though DCS is a long-term sound alternative, the huge investment cost required to build its infrastructure may hinder its adoption in some areas. It was found that 60% of systems investment cost is attributed to its distribution network [22]. This suggests that the structural optimization of a DC network is paramount and well justified. Despite this highlighted importance, the current literature dealing with the structural optimization of DCS is relatively scant. In this dissertation, we address the problem of optimizing the design and operation of a DCS. More specifically, given a set of customer buildings with known time-dependent cooling demand, we seek to determine the sizing of the chiller plant and storage tank (if any), and the size and layout of the main distribution network, so that the total investment and operational costs are minimized. It is worth noting that the optimization of in-plant design and operations is not considered. Towards this end, we address the optimization of a DCS design while capturing structural constraints as well as both pressure-and temperature-related constraints. More specifically, we make the following contributions:

- We develop two MILP models for the optimal design of DCS by specifying the chiller plant size, the storage tank size, the piping network size and layout, and the quantities produced and stored during each period of time while considering structural and technical constraints (including temperature- and pressure-related ones).
- We present the results of computational experiments that demonstrate the practical usefulness of the proposed models, since large instances require moderate CPU time.

1.6 Methodology

The very first step in our research is to form a comprehensive and design-oriented theory base for the system in hand. This is a vital step as it lays the ground for a full understanding of system's parameters, variables and constraints. Hence, it counts towards the full realization of a realistic and practically sound optimization models. In support to this, a literature survey was conducted reflecting design-related aspects of DCS while deeply reviewing existing DCS optimization-focused body of knowledge. In parallel to this, our understanding of the system was further verified with experts working in the field of DCS in Qatar, specifically, in the area of DC networks and piping systems. Following this, graph theory was used to structure and formally describe the district cooling network under study. To formulate the problem, Mixed-integer Linear Programming (MILP) was used. Given the system's complexity, part of the problem that we were dealing with had the structure of a Mixed-integer Non-linear Programming (MINLP). In this case, the Reformulation-

Linearization Technique (RLT) was used to restate the MINLP into a MILP. Developed models were then coded and tested using a commercial general-purpose solver (CPLEX). Given that all our attempts to get real-life instances have fallen short as companies refused to share data due to their claimed sensitivity, hypothetical data were generated and then used to test the validity of the model while incorporating the full sense of what is realistic and what is not based on our verified understanding of the real system.

1.7 Thesis Organization

The thesis report is composed of six chapters including the current introductory one. The remainder of this report is organized as follows.

Chapter 2 provides background description and literature review pertaining the problem in hand as retrieved from the current body of knowledge. It provides a theory base for system's components and design related aspects. It also gives a comprehensive but focused review of DC network optimization related literature.

Chapter 3 provides a formal description of the problem setting and assumptions. This chapter is organized in 3 sections and presents the basis for our modeling framework. It aims at describing all aspects (including assumptions and limitations) related to the structural and technical characteristics of a DC network.

Chapter 4 presents MIP models that are built upon the provided description in Chapter 3. In this chapter, a MILP model is presented to address the plant design and operations problem. Similarly, a MINLP model is formulated for the network design problem and then restated into an equivalent MILP formulation with the aid of the Reformulation Linearization Technique.

Chapter 5 presents the results of a computational study that aims at demonstrating the practical usefulness of the proposed models. The MILP models described in the previous chapter were coded, and then implemented and tested on instances of various sizes with the aid of an optimization software package; namely, IBM ILOG CPLEX 12.5. The performance of solving models to optimality and using MIP-based heuristics is reported. Then, the impact of changing some design parameters on the performance of proposed models is presented.

Chapter 6 highlights key concluding remarks and future research directions.

Chapter 2

Background and Literature Review

This chapter provides a comprehensive and contextualized review of DCSs, with an emphasis on design and optimization related literature.

Section 2.1 begins with an overview on the history of DCSs and how they evolved. Section 2.2 highlights the benefits of DC from both environmental and economic perspectives to illustrate why such system is worthy for investigation. Following this, a design theory base is presented in both Sections' 2.3 and 2.4, where system's components and its related technical consideration are discussed in depth. Such theory base presents a critical piece in the literature survey where all network design aspects are addressed to ensure forming a full understanding of the system, and eventually, enable its proper and realistic modeling. Section 2.5 includes a focused review on all optimization related efforts in the area of DC network optimization. The chapter is wrapped up with a summary that features all mentioned efforts, highlights the significance of the dissertation in hand and how it fits within the current body of knowledge.

2.1 Emergence of DCSs

The concept of district cooling is derived from the concept of energy distributed systems, in particular, form district heating systems. Looking back over history, one can notice that DCS has its root in the nineteenth century when it was commercially available for the first time in the United States; yet, its concept goes back to late 1880s [23] [24]. Prior to this, the first application of district systems was initiated in the 14^{th} Century when French citizens developed one geothermal district heating system which is still in continuous operation and known as Chaudes-Aigues Thermal Station [19]. Table 2.1 illustrates the historical evolution of DCSs.

Table 2.1: Historical Evolution of DCSs

Year	Key Related Events
1880s	• Plans were developed to distribute clean cooled air using underground piping systems.
1889	• District cooling was introduced practically in Colorado Automatic Refrigerator Company in Denver, United States.
1930s	• Cooling systems were built in both New York City and Capitol buildings, United States.
1960s	• First district cooling systems were commercially introduced in the United States.
1967	• First district cooling system in Europe which supplied district heating and cooling to the La Dfense office complex in Paris, France.
1980s	• District energy systems were built in Japan, South Korea and Malaysia. • First DCS was installed in Scandinavia, including Denmark, Norway and Sweden.
2000s	• Large district cooling systems were built in the Middle East to cope up with the rapid real estate development especially in Abu Dhabi and Dubai.

Noticeably, district cooling system is not a breakthrough concept rather it is a derived model originated from the concept of District Energy Systems (DESs). In simple terms, district cooling system is one type of DES.

Following different grouping schemes, DES can be categorized based on several aspects; such as transport fluid, thermal energy transported, type of energy source and application and market served [19]. Table 2.2 below illustrates these classifications.

Table 2.2: Classification of DESs

Category	Type of DES
Transport fluid	• Low pressure steam • Hot Water • Chilled Water • Air
Purpose *(Thermal energy transported)*	• Heating • Cooling • Heating and cooling
Type of Energy Source	• Conventional energy • Renewable energy • Combined heat and power plants • Waste heat
Application and market served	• Density populated urban areas • High-density building clusters • Industrial Complexes • Low-density residential areas

It can be noticed that DCSs fit under DESs in the functional hierarchy. Therefore, reviewing DES is useful to form a comprehensive understanding of its applications, of which district cooling system is one of them.

Soderman and Pattersson (2006) defined DES as an interact system which consists of a group of energy suppliers and consumers, district heating pipelines, heat storage facilities, and power transmission line in a district [25]. It is worth noting that in their study, the term "energy" was used to reflect only heat and power, which is not always the case. As delineated by Razai and Rosen (2012), DES was defined as a centralized local thermal energy system, which has the function of (i) producing hot and/or cold fluids; (ii) and then distributing them throughout a region [19]. Given the above mentioned definitions, energy services provided by a DES can be in the form of space heating, space cooling, water heating and/or electricity/power generation [26].

Being classified as types of DES, systems such as district heating and district cooling systems are expected to share similar characteristics in terms of structural, technical and operational features. Conversely, they are expected to exhibit sort of variations as each of them serves different customer requirements (for instance, cooling versus heating). To this end, it is worthy to highlight these differences to help understand as to why designing a district cooling network differs from designing any other network such as district heating network. This will be done by technically addressing the production process defined in Section 1.1.

The production process encompasses the mechanical and thermal activities needed to produce the heating/cooling medium at a certain temperature, which varies according to the service requirements. The subsystem that houses all equipment and chemicals is called heat source in the case of district heating systems and cooling source in the case of district cooling systems [27]. In practical means, the cooling source can be called chilling station [5], chiller plant [6], central chiller plant [28], chiller systems [15], central refrigeration plant [29], and cooling plant [30]. In our study, the term chiller plant is used henceforth.

Technical aspects related to day-to-day activities carried in plant, along with the type of equipment used to generate the final output have no direct impact on the design of a district network. To put it more simply, the plant, including all its operations and equipment, is viewed as a black box when addressing a network design problem with a single source. Nevertheless, what matters here is the plant interaction with its surrounding as this may impose certain limitation regarding plant location; which eventually influence the network design. As the plant is one part of an interconnected system, two possible linkages can be found in the upstream and downstream of the plant as explained below.

1. **Interaction with the external environment:** this subsystem needs two key inputs to be brought into operation, that is, it needs energy sources to run its equipment. These energy sources can be in various forms and available in particular locations. Thus, if the location is to be selected after defining the plant technologies, this will impose limitation on the set of possible locations for placing a plant. Similarly, the type of cooling/heating medium can govern the site selection. For instance, it is better to not to locate a chiller plant far from the sea front if water is used as a cooling medium [29].

2. **Linkage to other internal subsystems:** the production plant is connected to another two systems, the distribution and the storage systems. The physical connection between them is nothing but the piping network which transports the cooling/heating agent. The thermal characteristics of this agent have an impact on the network configuration. Obviously, a considerable difference is found between heating and cooling mediums when it comes to thermal aspects. This impact is more critical to the case of district cooling systems as they operate with significantly lower temperature differential than district heating systems, which generally operate with temperature differential greater or equal than 40 Degree Celsius [27].

2.2 Environmental and Economic Benefits of a DCS

In the current environment of high technological dynamics, DCSs have been attractive and functional throughout various parts of the world. Enabled by its distinctive features, this system is capable of providing commercial and social values to both its users, and the society at large. System's attributes can be reflected in two terms: (i) centralization; and (ii) flexibility. These two attributes are the reason behind the ability of the system to introduce economic and environmental advantages to the community and its users as detailed in what follows.

2.2.1 Environmental Benefits

The ecological dimension is becoming increasingly important in today's carbonized environment. Global and regional initiatives, such as the Kyoto Protocol, have stressed the urgency in adapting new cooling solutions to conform to the stricter environmental standards [24]. As a matter of fact, the wise use of fuel sources and energy conservation technologies are the most effective ways to reduce atmospheric emissions, global warming, and the release of ozone depleting gases [27]. Substantially, the application of DCSs presents an opportunity to produce the required cooling energy while being consistent with the current environmental needs [27].

District cooling systems stand as a flexible technology that allows the use of various energy sources. This flexibility facilitates the use of non-carbon energy forms for cooling purposes which eventually leads to reduction in GHG emission [19]. For instance, there are settings that allow the use of sources other than electricity to drive chillers such as free cooling and combined heat and cooling plant, which results in less CO_2 emissions [4].

Furthermore, these systems are based on the principle of centralization. Chow et al. (2004) stated that DC allows a massive and collective cooling energy production which makes the system more energy efficient than a conventional cooling system when installed at individual buildings [28]. This indicates that such system has an energy saving effect as it entails the use of less energy to supply the same service requirement, while reducing CO_2 emission. This is explained by the fact that the thermal capacity of a DCS necessitated to supply n buildings is less than the sum of capacities of individual cooling systems if installed independently in the same n buildings [6] [31]. In addition to this, Chan et al. (2007) explained that it is easier to control pollutant emissions and wastes from a remote centralized district plant site than from scattered plants over a district, which eventually yields to more environmental benefits [31]. Hart and Rosen (1996) studied the impact of several utility-based district cooling scenarios in view of both environmental and health aspects [15]. Their findings proved that DC reduces the ecological impact by means of reduced coal consumption, air pollution and acid deposition. Interestingly, Genchi et al. (2010) proposed a CO_2 payback formula to assess the environmental impact of a district energy system in Japan [32]. The study simply utilized the concept of payback period to understand the net environmental impact resulting from the use of district energy system.

Another environmental perspective is presented in the improved aesthetics along with the reduced noise at local premises [7]. In addition to this, having a cooling systems operating outside the building leads to eliminating the use of chemicals locally; therefore, offers improved health conditions for users.

2.2.2 Economic Benefits

In the current competitive business environment, placing premium attention on such green initiative is not fully merited if not coupled with economic benefits. Clearly and as mentioned earlier, the consolidated production scheme in a DCS allows tapping into the economy of scale; hence, making it a more energy efficient alternative when compared to operating building-specific cooling systems [29]. Evidently, Ka-Wing (2002) identified a 32% reduction in energy usage for cooling purposes when replacing the individual air conditioning systems operated at non-domestic buildings in South East Kowloon Development area, Hong Kong, with a DCS [10]. This can be translated in monetary values to about HK$ 40 million savings per year. Likewise, a study conducted by Poeuf et al. (2010) aimed at comparing the energy performance between stand-alone chillers and DCS in Paris and the obtained results showed a 47% reduction in electricity consumption as a result of using DCS [33].

More essentially, the economics of DCS are not only inherited and granted; rather, they are planned and obtained. In true means, further savings can be realized depending on the selected structural and operational settings. It is worth noting that there is no absolute guidance in what is the most cost-effective setting to adopt, rather, it is case specific and driven by district nature and parameters. For example, operating a DCS using absorption chillers allows the utilization of cheaper energy sources like steam, waste heat and solar energy. Hence, results in a less expensive operating cost. Albeit its cost-saving attribute, this technology may not be always selected due to its low operational efficiency, which is not desirable in some settings. Another example is installing a storage tank, which can bring in more economic savings through allowing the production during non-peak hours and then using it when cooling demand is at its peak. However, the inclusion of such tank is not always economically justified, as it depends on both the diversity of customers' demand, and the power tariff structure when operating electricity-driven chillers. For instance and while they were investigating the feasibility of building a DCS on a reclaimed land in Hong Kong, Chan et al. (2004) found that including a TES is not economically attractive given that only non-domestic customers were considered (low load diversity), and the power-tariff structure had no major differences between day and night [29]. Towards this end, optimized schemes are essential to exploit further economic benefits of DCS.

2.3 System's Components and Design Considerations

In common with other cooling technologies, DC aims at providing space-cooling services to various types of customers. Uniquely, the service provision of this system is done through mass production [29]. It means that a substantial cooling energy production is enabled to provide air cooling services to a group of buildings [31]. From a complexity perspective, district cooling system can be classified as an array that contains multiple subsystems. The integration of all subsystems is essential to achieve the system's optimum performance in terms of both operations and economics [27]. Therefore, integrative decisions should be made from the early stages of systems development; particularly, from the planning and design phases. To build a rigid ground for understanding all network design aspects, system's components and system's design parameters are discussed in what follows.

As indicated in Section 1.1, a DCS is an array of interconnected systems, including chiller plants, distribution networks and scattered consumers' substations. In Chow et al. (2004) study, chiller plants were decomposed further into two systems to contain parallel chillers and pumping stations [6]. Similarly, other studies by the same authors included the heat rejection system as a separate entity [29] [28]. To this end, there was no major difference between all explored structures as all of them contained the same set of entities but with different grouping schemes.

All in all, it was commonly found that three main modules are necessary to form a DCS, namely, (i) chiller plant(s); (ii) distribution system; and (iii) customer's substations. Moreover and as found in some recent studies, a DCS can be additionally configured with a fourth optional subsystem, being a storage tank [5] [27]. A work breakdown structure of this system is illustrated in Figure 2.1 below including the three basic elements along with the storage tank. Each subsystem is discussed in details in what follows.

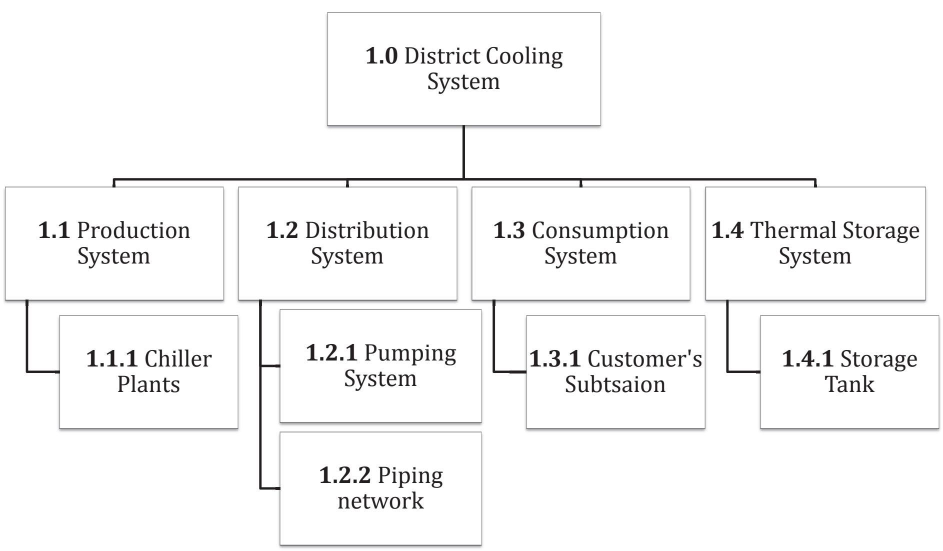

Figure 2.1: Main Components of a DCS

2.3.1 Chiller Plant

The functionality of a district cooling system is solely dependent on its chiller plants. Through their in-house operations, chiller plants have the capability of generating cooling energy for air conditioning use [29]. Hart et al. (1996) describe such a plant as the central facility in a district cooling configuration, with a role of producing the entire cooling capacity [15]. From a network design perspective, there are two elements related to a chiller plant; (i) plant location; and (ii) plant size/capacity. Design considerations related to each element are discussed below.

- **Plant Location**

  According to Yildirim et al. (2010), location of production plant is very important as it controls the pipe length, pressure loss and consequently the whole system cost [34]. Thus, making a decision as to where to locate a chiller plant is critical and, of course, constrained. Considerably, the set of potential sites for chiller plants are controlled by both the type of cooling technology used in the plant, and the governmental regulation. It is also restrained by the available unoccupied sites (availability of free land space).

  Recalling from Section 2.1, cooling technology used may impose certain constraints when designing the distribution grid because of the interconnected nature of the system. For instance, chiller plants powered by water may essentially need to reserve sites near the coast. Therefore, exploring a bit about cooling technologies used in these facilities helps to narrow down the potential options for facility location.

  Skagestad et al. (1999) explained that there are four cooling technologies that can be used to generate cooling agents: (i) compressor driven chillers (also known as vapor-compression chillers); (ii) absorption chillers; (iii) ice slurry; and (iv) ambient/free cooling [16]. A comparison of the first two types, with regards to fields related to network design, is illustrated in Table 2.3 below. The technology of free cooling is not detailed as its idea is relevant to countries with cold climate because it utilizes the deep lakes, rivers, sea, and oceans as its source of cold temperature fluid [27].

Table 2.3: Comparison between Two Types of Cooling Technologies

	Compressor-driven Chillers	**Absorption Chillers**
Energy driver	Electric motors, gas turbines, steam	Direct-fired (typically natural gas and electricity), Indirect-fired: steam, or hot water from a solar array; waste heat
Refrigerant	R22, R-134a, R-123, Ammonia	Water, Ammonia-water solution;
Cooling medium	Water	Lithium Bromide (LiBr), Water
COP	4 - 5	0.65 - 1.2

- **Plant Capacity**

Razaie et al. (2012) explained that a thermal production plant capacity can be verified by both customers' loads and heat losses in the system [19]. It can be also influenced by the availability of multiple plants serving the same district. Typically, the cooling demand within a district can be satisfied either by a single chiller plant or multiple chiller plants. Yet, it is always questionable whether to have one large plant far away from some customers or smaller multiple plants closer to individual customers [25]. In the case of district cooling system, this decision is governed by the total cooling demand, the desired system performance level and the initial available capital investment. Powell et al. (2013) expressed that operating with multiple chiller plants is desirable as it introduces redundancy to the system and helps in both satisfying all cooling demands while enhancing the overall reliability of the system [5]. Additionally, there is a relationship between the chiller's capacity and its performance. Generally, the performance of chillers is defined by the amount of heat removed from the space being cooled to the energy input consumed to drive the chiller. This measure is known as Coefficient of Performance (COP). The COP of a chiller increases as the capacity increases until reaching a certain level in which there will be no significant increase in COP beyond [29]. This may act as a constraint when defining the chiller plants' capacity in the case of multiple-plants setting.

2.3.2 Main Distribution Network

Bahnfleth et al. (2003) defined distribution system as a piping network through which the cooling medium is transferred by one or more pumping systems [35]. Similarly, Chow et al. (2004) cascaded the distribution system into pumping scheme and distribution network [29]. In this subsection, the common forms of both pumping and distributions systems are discussed along with their related network design considerations.

2.3.2.1 Pumping System

Basically, a pumping system is utilized to dispatch and circulate chilled water by means of creating pressure differential between the supply and return pipes [27]. It includes one or more pumps that can be located at chiller plants, distribution networks, and/or customer substations. The general categorization of chilled-water pumping scheme includes three types: (i) primary pumping (also known as centralized pumping); (ii) primary-secondary pumping; and (iii) distributed pumping [29]. Pumps can operate at either constant or variable flow [35]. This variation in flow introduces savings in pumping energy requirements, especially when it is combined with variable speed valves [27]. Additionally, the pumping energy consumption is influenced by the piping size, and the flow rate of thermal carrier [36]. The impact of both location and capacity of the pumping system on the network design is discussed in what follows.

- **Pump Location**

  In the primary pumping scheme, a single pumping system is used to distribute chilled water to all customers within the system [29]. Whereas in the primary-secondary pumping scheme, two pumping systems are used; one at the production plant, and the second at the beginning of the distribution loop [29]. Both schemes are illustrated in Figure 2.2 below.

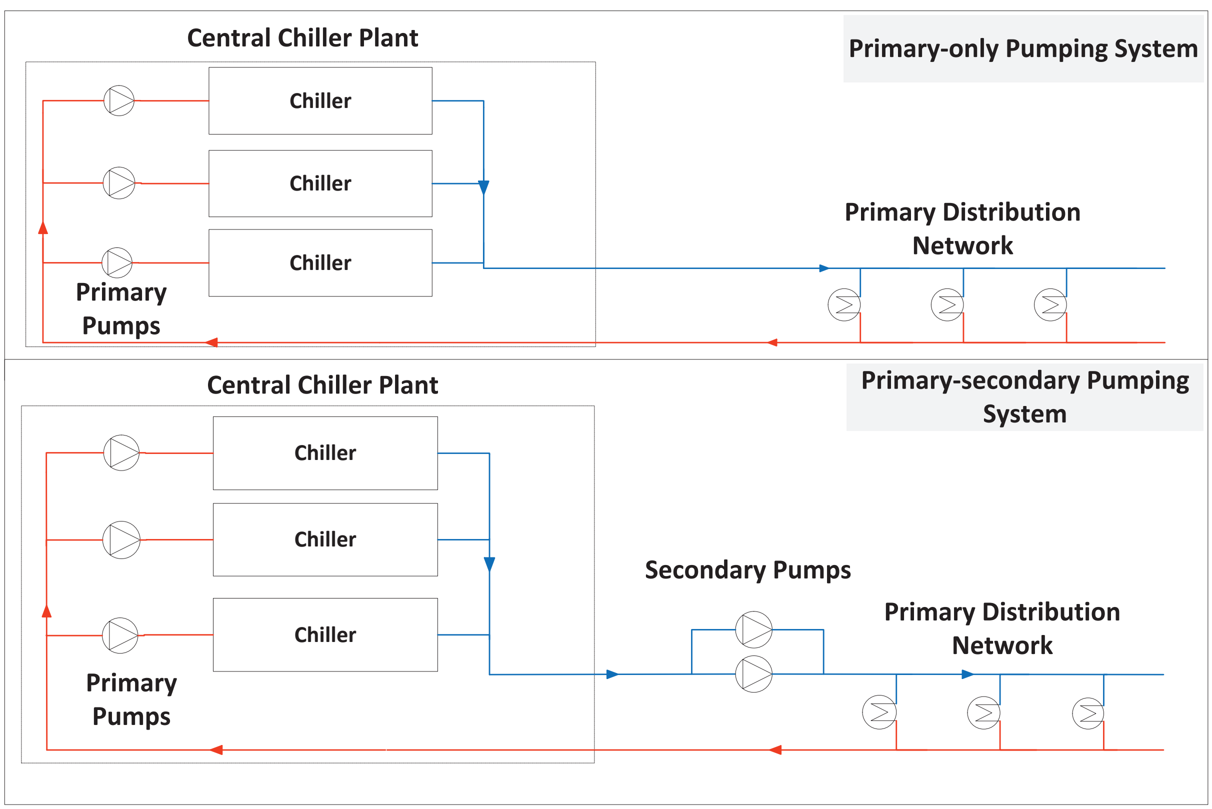

Figure 2.2: Possible DC Pumping Schemes

In the case of distributed pumping, a primary pumping system is installed in the chiller plant, along with a pumping system at each distribution branch [29]. Therefore, pumps locations are tied to the location of both chiller plants and customer's substations; that is, their location is a subsequence of both chiller plants and customers' locations. For instance, the pumps in the primary setting are included as entities within production system; more precisely, they are located inside the chiller plant [37].

- **Pump Size**

  Pump sizing is crucial to ensure sufficient flow of chilled water to all customers' substations on timely manner. According to Pirouti et al. (2013), pump size is calculated based on the maximum pressure drop for the most remote customer in the network [36]. This pressure drop is often found in the longest run in the system; however, it is not always the case [38].

  Chan et al. (2007) termed the route in which the pressure drop is the highest as the critical path and used the Darcy formula to calculate its corresponding head loss [31]. Similarly, Taylor et al. (2008) stated that the pressure loss in the critical circuit defines the required pump head which drives the annual energy consumption [38]. Therefore, the pump head should be sized in such a way that ensures the supply to the most critical customer in the system.

2.3.2.2 Piping Distribution Network

The cooling medium produced at chiller plants is distributed to customers via piping network. For this reason, the knowledge of both the piping structure and configuration along with the cooling medium attributes are important.

Key design aspects related to both operational and structural attributes of distribution networks are discussed in what follows.

- **Pipe Material and Insulation**

  A pipe is a hollow cylinder that is made of one primary layer of material with specified thickness. Essentially, selection of piping material depends on both its cost and the characteristics of cooling medium being carried and transported [34]. The most common distribution pipes are made of steel due to their ability in preventing leakage [29]. Beside welded steel, polyethylene (HDPE) is commonly used for chilled water piping systems [27].

  Clearly, one of the critical design elements in energy distribution network is the heat loss [19]. Heat gains or losses are not only an economical waste but they also have an impact on the overall system performance. Consequently, a second layer called insulation is usually added as a coating on the first layer of a pipe. The main trait of insulated pipes is to reduce the unnecessary energy consumption resulted from heat losses/gains. In northern climate zones, insulation for underground piping system is not required as there are generally small temperature differences between the chilled water running in the pipes and the surrounding soil temperature [27]. In the contrary, insulated pipes are crucial in warm climates due to the high ground temperature. For that reason, it is necessary to reduce excessive heat gains which cause undesirable rise in cooling medium temperature, and eventually, affecting the overall system's cost and performance.

- **Pipe Installation**

  Pipes can be either installed above the ground level or buried underground. Although aboveground piping networks are attributed by the ease of accessibility for any maintenance tasks, they are subjected more to damage [34]. Additionally, aboveground or non-buried installation should be always insulated and protected against any vapor condensation on its surface [27]. Hence, underground piping networks are commonly used as they are aesthetically more pleasant and safe [34]. This type of installation can be either directly buried into soil or inserted in concrete tunnels then buried [34].

Another aspect related to pipe installation is pipe's elevation. Pipes can be installed horizontally or at a certain elevation. In case of downward flow, pipes installed from a higher to lower elevation can help in reducing pump power, but are subject to complication of gravity analysis during design phase as pressure drop becomes a function of both friction and gravity [30]. In case of DCS pipelines, issue of elevation becomes even more complex as it include the analysis of two-parallel pipelines that carry flow in opposite direction (supply and return).

- **Piping Network Layout and Connection Schemes**

  Piping layout is the structural configuration of the distribution network with the function of transporting the cooling effect to the end-user. Generally, the configuration of these networks can be found in three forms, being (i) tree shaped networks; (ii) radial networks; and (iii) looped networks [28]. An illustration of these topologies is given in Figure 2.3 below. Each of these schemes can be either applied exclusively or in joint with the other types [31]. Yet, it is worth noting that most commonly, these types are found in integrated manner [28]. Therefore and depending on the adopted topology, cooling demand can be satisfied either (i) directly from the cooling source (chiller plant and thermal storage); (ii) via district cooling mainlines, and (iii) via sub-lines connecting different customers.

Likewise, cooling loads can be transported to thermal storage tanks either directly from chiller plants or through mainlines [30].

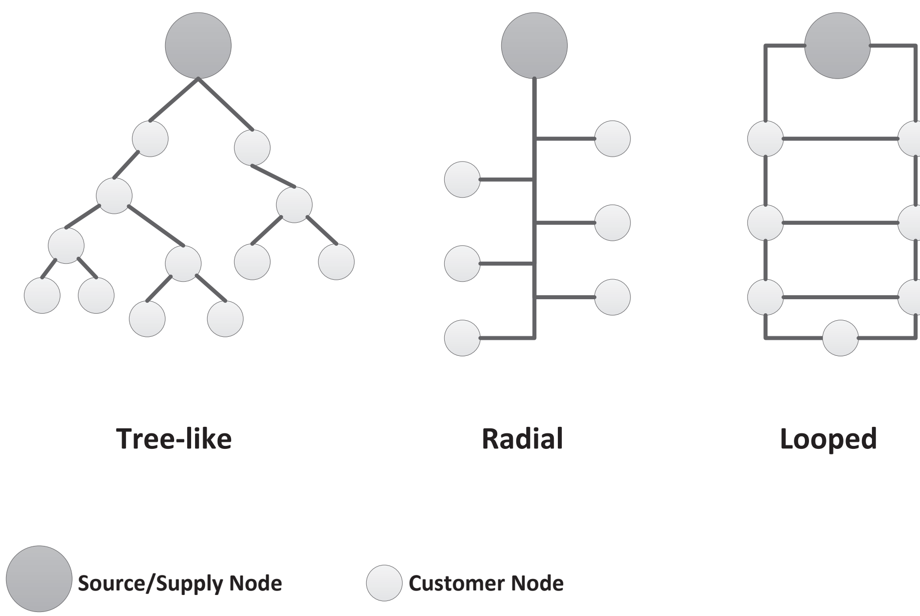

Figure 2.3: Possible Network Configurations

- **Pipe Size and Length**

  Pipe sizing plays key role in optimizing the overall system economics and performance. By optimizing their dimensions, pipes can supply the right amount of cooled air to end users at the right time with reduced cost. For this reason, pipe sizing is considered as an important aspect in optimizing cost and/or performance in networks. According to Skagestad et al. (1999), four key factors direct pipe sizing criteria: (i) temperature differential (ΔT); (ii) flow velocity of cooling medium; (iii) pressure at the design load conditions; and (iv) pressure differential for the most remote customer pipes [27].

The impact of these factors on the pipe size or vice versa are discussed below.

- **Temperature Differential (ΔT):**

  In piping network design, large ΔT is desirable as it allows the use of smaller pipes. This is explained by the inverse exponential relationship between the pipe diameter and ΔT for a given pressure gradient as illustrated by Skagestad et al. (1999) [27]. Generally, temperature difference in district cooling distribution networks ranges between a minimum of 6^oC to a maximum of 11^oC [27] [39]. For that reason, control of ΔT is more critical in district cooling system than in district heating systems as the latter operates with much higher ΔT ranging from 40^oC to 50^oC [30].

  In principle, temperature differential is a function of both supply and return temperatures; that is, $\Delta T = T_{return} - T_{supply}$. Where T_{supply} and T_{return} corresponds to the temperature of the cooling medium being transported to and from the customer substation (or chiller plant), respectively. Typically, T_{supply} is stipulated in advance in a form of a contract between the supplier and the customer [27]. As such, supply temperature represents a constraint on design of a DCS as it reflects important part of customer requirements.

- **Flow Velocity and Rate:** Fluid flow rate is tightly related to the cooling load required by customer's substation to satisfy their cooling demand. According to the basic concepts of fluid mechanics, flow rate is a function of cooling fluid velocity. Their relation is known as $Q = vA$, in which Q denotes the volumetric flow rate, v

is the fluid velocity, and A is the cross-sectional area of the pipe. Taylor et al. (2008) expressed that flow velocity is considered as limiting factor to pipe sizing [38]. This is explained further by Feng et al. (2010); who expressed that a maximum fluid velocity should be defined to ensure the hydraulic stability in a DCS [40]. Practically, this velocity is to be controlled by either constant or variable speed valves installed at the pumping systems.

– **Pressure Loss:** Pressure loss is a key design parameter due to its impact on both the investment and operational cost of a district cooling system [34]. The opposite is also true as the pipe sizing has an impact on the pressure loss in the system. Pirouti et al. (2013) stated that pipe size has an impact on the pressure loss, and consequently on the energy consumed for pumping [36]. Therefore, its relationship to pipe's diameter and length makes it a very critical factor in network design problems. More details to the pressure-related characteristics of the system is discussed in Section 2.4.2.

2.3.3 Customer Substations

DCSs serve various types of customers' buildings such as family residences, commercial buildings, schools, offices, leisure facilities, or hospitals. Regardless their types, cooling solutions are ultimately designed to meet their requirements. Basically, customer's building size defines the cooling load to be produced and supplied by the system and customer substation is the connection between customer buildings and the system, which is also known as customer interface or Energy Transfer System (ETS). In network design, three aspects are related to customer's substation: (i) location; (ii) cooling demand; and (iii) connection type to system, and are discussed in what follows.

- **Location**

  Practically, customer's buildings are defined with fixed location [30]. Customer's location can be expressed in coordinates that serve as inputs to a network design problem.

- **Cooling Demand**

  Given that DCSs supply a variety of customers with cooling services, data related to air cooling consumption is needed for designing the system and network. As current cooling demand is satisfied by electrically driven air conditioning system, energy consumption data can be filtered and used to reflect the cooling consumption pattern. This type of data can be obtained either from a local energy utility (given the customer permission) or directly sought from the customer. According to Church (2007), three consumption data are needed for each customer's building summarized as follows [41].

  - **Peak demand:** to size production plant and determine customer's connection requirements;
  - **Annual consumption:** to identify the economic feasibility of the whole system;
  - **Daily usage profile:** to plan the chiller plant day-to-day operations

- **Connections to System**

  Two types of connections are used to link customers to the system. Typically, customer's substations are designed for either a direct or indirect connections that are used to link customers with the system. In a direct connection, cooling fluid is transferred directly to customer's own Air Handling Units (AHU) coils, fan coil units, induction units, HVAC system etc. Whereas in an indirect connection, single or multiple heat exchangers are utilized to transfer heat to the building. The selection of heat exchange depends on the pressure differential requirements. Relevantly, Skagestad (1999) explained that the higher the pressure drop, the smaller and less expensive the heat exchanger will be needed [27]. Therefore, the differential pressure across customer's ETS is a crucial design parameter, and is detailed further in Section 2.4.1 below.

2.3.4 Thermal Energy Storage

TES presents an optional inventory system in a DC setting. Its main function is to stock energy for future use by shifting the produced and unutilized chilled water during non-peak hours for usage during peak hours. This enables the full utilization of the production system capacity at all points of times, while allowing its design near to the average thermal load, and not at the peak one [27]. Therefore, TES is commonly configured within DCS not only because its often contribution in reducing total system's cost, but also due to its role as an energy-saving technology.

There are three TES technologies that can be potentially utilized in DCS, namely: (i) sensible heat storage - where chilled water is stored in its original form, (ii) latent heat storage - where chilled water is stored in another form such as ice, and (iii) thermo-chemical storage - in which the storage process is based on chemical reactions [42].

Moreover, there are two TES types based on its functional time-frame [46]. They are: (i) long-term storage (also known as seasonal storage) and; (ii) short-term storage (also known as night-to-day storage). The seasonal storage allows the use of various energy sources that can be effectively utilized only during specific periods of the year. For example, free cooling can be used in winter to produce chilled water, which is stored for usage during summer (when cooling requirements are relatively higher) [43]. Additionally, night-to-day storage allows producing chilled water during night (when cooling requirements are relatively less depending on the customer nature), then discharging it during day time (when weather is relatively hotter). Regardless the adopted technology, what of a designer's interest is at what size to install a TES. More essentially, whether operating a TES is economically viable or not. Despite its noticeable advantages and as discussed earlier in Section 2.2.2, its inclusion in a DCS is not always justifiable and is case dependent. Pertinently, Chan et al. (2006) tested the impact of integrating TES in a DCS scheme and operations [44]. By using simulation methods, they assessed both the cost effectiveness and energy savings that could be possibly reaped as a result of including such technology. A case on Hong Kong was taken as an example. The results showed that 40% of the peak load is the optimal size of a TES to operate with. However and given the illustrated tariff structure and payback period, incorporating a TES was not economically attractive.

2.4 Technical Considerations of a DCS

2.4.1 Hydraulics Characteristics

According to Yildirim et al. (2010), the pressure loss per unit length, is viewed as a common design parameter in piping networks, together with pipe materials and installation types [34]. Technically, pressure drop is one of the most important features pertaining flow in pipes [45]. Indeed, the change in pressure values while transporting chilled water from one point to another is unavoidable. Thus, a proper control of it is mandatory to ensure the right delivery of chilled water to all customers' locations.

Boysen (2003) stated that the absence of a hydraulically balanced system could result in either a high unnecessary rate of circulation or inability to supply and serve certain customers in the system [39]. Both consequences are totally undesirable. They present a waste of energy and money in the first scenario, and a failure of service in the latter one. Clearly, the pressure loss in piping networks has impact on both the system's investment and operational costs. For example, the result of operating a piping system with high pressure loss per unit length, is an increased operational costs (presented in pumping pressure) and a reduced investment costs (presented in smaller pipe size) [34]. Therefore, pressure-related considerations are critical elements in the design of a DCS.

As discussed earlier in Section 2.3.2, the design of piping/distribution network has impact on the pressure losses in the whole system and vice versa. Two types of pressure losses can be experienced in any distribution system; namely, major losses, and minor losses. Moreover, pressure drop is also continued to take place across customer's substation. All these points are investigated and detailed further in what follows.

2.4.2.1. Major Losses in Primary Distribution System

According to Wilkes (2006), pressure drop is directly proportional to the length of the pipe [46]. It simply indicates that the longer the piping network is, the higher the resulted pressure drop is in the system. In the contrary, there is an inverse proportionality between pressure drop and pipe's diameter. Yildirim et al. (2010) explained that the smaller the pipe diameter is, the higher the pressure loss is in the system [34]. This relation can be confirmed further by the Darcy equation used by Chan et. al (2007) to calculate the pumping requirements [31]. This type of pressure loss is classified as major loss and can be calculated using Equation 2.1 [45].

$$\Delta P_L = f \frac{L}{D} \frac{\rho v^2}{2} \tag{2.1}$$

Where ΔP_L is the pressure drop through pipe (Pa), f is the friction factor (dimensionless), L is the pipe Length (m), D is the pipe inside diameter (m), ρ is the fluid density (kg/m^3) and v is the average flow velocity (m/s).

Similarly, the equivalent major head loss can be quantified using Equation 2.2 below [45].

$$H_{L,major} = \frac{\Delta P_L}{\rho g} = f \frac{L}{D} \frac{v^2}{2g} \tag{2.2}$$

Where $H_{L,major}$ is the head loss to friction (m), ΔP_L is the pressure drop through pipe (Pa), ρ is the fluid density (kg/m^3), g is the gravitational constant (9.81 m/s^2), f is the friction factor (dimensionless), L is the pipe Length (m), D is the pipe inside diameter (m), and v is the flow velocity (m/s).

Once the pressure loss (or head loss) is determined, the required pumping power to overcome these pressure losses can be calculated. This is very essential to guarantee the delivery of chilled water to all customers' substations. In true means, the pumping head is always determined based on the critical path to allow the delivery to all customers including the furthest one [31]. This can be calculated using Equation 2.3.

$$W_{pump} = \dot{V} \times \Delta P_L \tag{2.3}$$

Where W_{pump} is the pumping power (hp), $\dot{V}$ is the volume flow rate (m^3/s) and ΔP_L is the pressure loss through pipe of length L (m).

2.4.2.2. Minor Losses in Primary Distribution System

In long networks, the use of components such as fittings, valves, bends, tees and elbows is very common. These components alter the smooth flow of chilled water and forms what is called minor losses. These minor losses can be calculated using Equation 2.4 below.

$$H_{L,minor} = K_L \frac{v^2}{2g} \tag{2.4}$$

Where $H_{L,minor}$ is the minor head loss (m), K_L is the minor loss coefficient, v is the flow velocity (m/s) and g is the acceleration of gravity (m/s^2).

2.4.2.3. Differential Pressure at Customers' ETS

The customer substation is part of the larger pressure system, which is the whole DCS in the presented case. Being the place where the energy is transferred from the distribution main to customer's cooling system, pressure drop is undoubtedly experienced across the connected customer's substation. This pressure drop takes place in the direction of the fluid flow and occurs in valves, channels, nozzles, pipes and heat exchangers housed within the ETS [47]. Therefore, it is vital to consider differential pressure across the ETS when designing a DC network to ensure its integration in the DCS.

In general means, the ETS shall be designed based on (i) the minimum and maximum differential pressure in the main distribution system (mainlines and branches), and (ii) the static pressure in the same system [48]. The latter design parameter occurs if the ETS is placed on an elevation above the height of the system. Typically, a foot of elevation requires around 0.43 psi increase in pressure to keep the system operating as per the design requirements [49]. These data will help when sizing the heat exchangers, control valves and other

ETS components in such a way that guarantees its compatibility with the other parts of the DCS, mainly, the main distribution network [3].

In their book, Hewitt et al. (1992) expressed that the design of a heat exchanger can be adjusted to fit into the overall system as required [47]. For instance, if pressure drop across a heat exchanger, which is a major part in any ETS, falls below the allowable levels, then the designer has the flexibility to resize the heat exchanger so that the minimum permissible differential pressure is not altered. This minimum pressure differential value is defined by the critical customer along every path. To put it more clearly, ETS closer to the chiller plant would have the advantage of experiencing a higher differential pressure [27]. As the fluid moves downstream, the allowable pressure drop becomes smaller so that the return pressure value of the system is not violated. By virtue of this, the most remote ETS located at a particular line defines the minimum allowable pressure drop across all connected ETSs located along the same line. For that reason, the pressure drop across any ETS should not go below the permissible pressure drop, defined as the pressure drop across the critical customer ETS [27]. More details on the relation of differential pressure across a TES, and pressure drop along pipes is given in Section 3.2.

2.4.2 Thermal Characteristics

Addressing the thermal facet of district cooling systems is paramount for both its operational and structural optimization. This is due to the fact that the function of such systems is solely based on their thermal attributes in which without a proper control of them, the system will not be of effective use. For that reason, the effect of heat transfer is worthy for investigation to determine what sort of thermal constraints district cooling systems may have to remain functional. To the best of our knowledge, one of the reviewed literature related to district cooling systems was concerned about heat gains in piping networks. Although all reviewed studies overlooked this aspect without mentioning any assumption of neglecting heat gains effect, general heat transfer theories pertaining dynamic flow in piping system confirms its subjectivity to heat gains. This is confirmed further by the fact that heat losses in district heating system were highlighted and addressed by several scholars as discussed in what follows.

According to Van Lier (2010), four main losses could cause heat losses in a district heating system [50]. These losses were identified as losses in buffering tanks, losses in primary networks, losses in secondary networks- also known as service lines, and other undefined losses. A heat loss analysis was performed in the same study showing that the majority of heat losses in the system were resulted from the secondary network, making around 70% of the total heat losses in the system. Additionally, the second highest grid that made around 24% of the total heat losses was found in the primary piping network.

In another application of district heating systems in Korea, Park et al. (2010) studied heat losses in secondary piping systems [41]. By the use of a simulation technique, different structural schemes of secondary pipelines were evaluated with regards to heat losses. Interestingly, authors showed that heat losses can be reduced by some sort of structural enhancement such as resizing pipes diameter and/or increasing insulation thickness. In the same study and for an existing apartment complex in Korea, it was shown that the heat losses from service lines were around 14% of the total annual heat supply. Although this is considered relatively very large when comparing it with heat losses resulted from primary networks, which accounted for around 4% to 5% annually in dense population area.

As part of their study in evaluating and comparing the Danish and German methods used in aggregating district heating networks, Larsen et al. (2004) tested both methods on a real district heating network in Copenhagen, Denmark [51]. In their test case, the primary distribution network utilized pre-insulated 8.3 kilometers piping system, with pipe size ranging from 48 to 356 mm. Even though the corresponding heat losses in this network accounted for only 3% from the annual demand of 42 GJ/m, heat loss was viewed as an important design parameter. Similarly, and in a study by Tol et al. (2012), heat loss was viewed as significant component that have influence on both the energy efficiency and the cost-effectiveness of district heating systems. These losses are affected not only by the operational aspects of the system, but also by the structural design of the physical network itself. Alongside the temperature of supply and return heat carrier, both pipe's diameter and employed insulation materials could contribute to the heat losses in distribution networks [36] [52].

Similarly Benonysson et al. (2000) focused their study on the operational optimization of district heating systems; they expressed that the actual heat loss per unit length depends on the difference between the temperature of the transported heating water and the temperature of the surrounding soil, insulation standard of the pipes, as well as the pipes' diameter [53]. Such notes suggest that thermal characteristics are important when optimizing the structural design of any district heating distribution network.

Having shared the same theory base, district heating and cooling systems are mostly alike with regards to heat transfer principles. To further confirm this, basic theories of heat transfer; mainly, heat gains in piping systems were reviewed.

In principle, heat transfer associated with dynamic fluid flow in a piping system involves one or more heat transfer modes; mainly, conduction, convection and/or radiation. Depending on system's conditions, single or combined mechanisms of heat transfer take place between the ambient environment and the cooling medium running in the piping system. Technically, heat transfer could be reduced by laying an insulation layer on the top surface of pipes. This is practically possible as insulations are characterized by low thermal conductivity that helps in reducing heat gains and maintaining the state of refrigerant as it circulates through the piping network [54].

When the surface temperature is lower than its surroundings, heat flows from the ambient environment to the external insulation surface by means of convection and/or radiation. It also flows from the outer surface through the pipe section by means of conduction until reaching its inner surface. Then it flows from inner surface to the cooling medium carried within the pipe by means of convection resulting in a potential increase of cooling medium temperature. It is important to note that heat transfer by radiation has two elements; (1) radiation due to temperature difference, and (2) radiation due to sunlight [54]. For that reason, only one element of heat transfer by radiation might be experienced in underground piping systems.

In their book, Welty et al. (2008) explained mechanisms of heat transfer separately along with their methods of quantification. In addition to this, combined mechanisms were addressed and their methods of calculations were expressed in three different ways; using total thermal resistance along the piping network, using overall heat transfer coefficient and using the shape factor. As the geometry of pipes follows a cylindrical shape, heat gains were expressed in terms of shape factor using following Equation 2.5 [40].

$$q = k \frac{2\pi L}{ln(r_o/r_i)} \Delta T \tag{2.5}$$

Where q is the amount of heat gains in Btu/hr, k is the thermal conductivity of insulation in Btu/h ft ^oF, L is the pipe length in feet, r_o is outer radius in inch, r_i is inner radius in inch, and ΔT is the temperature difference between inside fluid temperature and outside ambient temperature. When reviewing equations that reflect each of the heat transfer modes separately, it was noticed that quantification method given in Equation 2.5 reflects the effect of heat transfer by conduction only. For that reason, examples of heat transfer in piping systems were reviewed and it was noticed that amounts of heat transfers by both radiation and convection were small when comparing it to heat transfer by conduction [40]. Thus, amount of heat gains by conduction would represent a good approximation of the total heat gains in the piping systems as given in Equation 2.5.

The movement of chilled water, brine or any other refrigerant type is essential in all cooling systems. Whether this movement is in service-lines, in-plant piping systems, or distribution mains, the transported fluid is subjected to a change in the amount of heat or thermal energy it carries. Equation 2.6 below expresses the equivalent temperature rise in pipelines resulted from heat gains quantified in Equation 2.5 [45] [55].

$$\Delta T = \frac{q}{f \times \rho \times C_p} \tag{2.6}$$

Where ΔT is the temperature rise in pipeline in ^oC, f is flow rate in pipe in m^3/h, ρ is density of liquid, kg/m^3 and C_p is specific heat capacity of liquid, kJ/kg-C.

Moreover and as discussed earlier in Section 2.3.2, caution should be taken in regard to the difference between supply and return temperature of the chilled water. This is a very important design consideration due to delta T impact on pipe and pumps sizes, pumping energy and capacity of chillers. Therefore, limitations on how large delta T should be set is very important to be considered when designing a DC network. This is explained further in Section 3.3.

2.5 Optimization of a DCS

Indeed, and unlike the great attention given to District Heating Systems (DHSs), only few studies were devoted so far to investigate the optimal structure of a DCS. Clearly, the special characteristics observed in a DCS suggest having a customized optimization models that essentially differentiate it from any other energy distribution system. For instance, the type of cooling medium imposes certain constraints on the piping configuration. This is due to its thermal and hydraulic attributes such as temperature differential and pressure drop which eventually has impacts on both the design of piping system and overall system performance. Table 2.4 summarizes relevant efforts in the areas of DHCS and DCS.

Preceding efforts were devoted to the optimization of dual-purpose district systems. For instance, Sakawa et al. (2001) focused their study on the operational optimization of a DHCS [56]. They worked towards formulating an operational planning model that uses gas-driven boilers and electricity-driven chillers to satisfy the heating and cooling demands, respectively. A Mixed-Integer Linear Programming model was formulated to reflect the operational characteristics of the problem. A branch-and-bound approach was utilized to solve a single-period case, and found suitable. Whereas in a multiple-period setting of which the problem became relatively large, a genetic algorithm (GA) method found to be more efficient and was used, but yielding to an approximate solution. The developed model did not address any of the structural-related decisions, and limited the optimization scope to assess operational-related ones only. It also left out the option of operating a cold-storage tank as part of the assumed setting.

Prior to their contribution to the field of DCS optimization, Chow et al. (2004) worked on deriving a desirable DCS scheme that involved making deci-

Table 2.4: Summary of Relevant Studies in the Areas' of DHCS and DCS Optimization

Study	Application Area	Decisions Involved	Modeling Approach	Solution Technique	Solution Type
Sakawa et al. (2001) [56]	DHCS	Operational	MILP	Branch-and-bound and GA	Near-optimal
Xiang-li et al. (2010) [57]	DHCS	Structural	MIP	Standard GA	Near-optimal
Chow et al. (2004) [29]	DCS	Structural and operational (limited to chiller plant)	Simulation	Spreadsheet calculation	Approximate
Chan et al. (2007) [31]	DCS	Structural	MILP	GA with local search	Near-optimal
Soderman (2007) [30]	DCS	Operational and Structural	MILP	Branch-and-bound	Optimal
Feng and Long (2008) [58]	DCS	Structural	MIP	Single Parent GA	Near-optimal
Feng and Long (2010) [40]	DCS	Structural	MIP	Standard GA	Near-optimal
Augusto et al. (2013) [3]	DCS	Structural	Simulation and numerical methods	Exhaustive search method	Near-optimal

sions related to sizing equipment (chillers, pumps, and heat rejection systems), locating them, and defining operational parameters such as flow rates and power consumptions [29]. First, a dynamic simulation approach to derive buildings thermal loads was utilized and applied to a real case in Hong Kong. From this point onward, spreadsheet computations and analysis that involved making structural and operational decisions for the same case were carried (such as sizing chillers and pumps, outlining the best locations of plants and main distribution pipes, and defining flow rates in mainline and by-pass lines). As shown, their methodology did not utilize any optimization technique. Instead, it utilized energy modeling approach to assist in making decisions and help estimating the total energy consumption of system under study.

This was followed by one of the earliest attempts in the area of DC networks optimization, which was pioneered by Chan et al. (2007) who aimed at finding a near optimal network topology that connects a centralized chiller plant with consumer's building [31]. Their contribution rested on proposing and utilizing a modified version of genetic algorithm (GA) to provide a more efficient searching approach for near optimal solutions. Mainly, they incorporated a local search and looped local search techniques to enhance GA performance in finding a near optimal piping network configuration for a DCS. In their presented problem, Chan et al. (2007) considered the objective of minimizing both the fixed cost associated with building the piping configuration, and the pumping energy costs associated with running the plant operations. They assumed a flexible network scheme by allowing any type of networks (radial, tree shaped or combinations of both). Therefore, structural constraints were simplified to include only (i) a restriction on the number of links in relation to number of nodes (the common valid constraint in all piping network); and (ii) a restriction on not allowing any cycles between nodes. Noticeably, the formulated mathematical model did not reflect any of the special features of a DCS. Instead, it was more of a common and general representation for a piping network without any indication of special technical behaviors. Following their approach, they managed to test developed model on two instances in different sizes and mutation rates using a series of parametric simulation (first case with 8 customers, and the second with 16 customers). Their results proved that incorporating local search improve searching performance while improving the quality of solutions, without any guarantee of optimality.

In parallel to this, relevant work was done by Soderman (2007) who developed a Mixed-Integer Programing (MIP) model to find an optimal design of a DC network [30]. By implementing a branch-and-bound method, Soderman (2007) addressed the optimization of both structural and operational aspects of a DCS so that the overall annual cost is minimized. This includes both the annualized investment cost and running costs of chiller plants and their equipment, and main distribution pipelines (parts that are fully owned by the developer). Resulted solutions can aid in making decisions related to which chiller plants, storage tanks and pipelines shall be built, where to build them, and what are their corresponding dimensions (capacity of plant and storage, and size of pipelines). They also aid in specifying some of the operational parameters presented in how chiller plants, and storage tanks shall operate, and what flow rates are transported in pipelines during different periods of the year. Their assumed setting included the possibility of constructing multiple chiller plants and multiple tanks to serve a set of customers located in urban area. It also considered the options of either serving a customer by a DCS, or satisfying his demand by installing an individual cooling machine at his premises. All these decisions were subjected to common supply- and demand-related constraints, flow conservations constraints (known as enthalpy flow balance, and includes heat gains/losses), and power consumption constraints (in case of operating individual cooling machines). It can be noticed that no technical constraints were considered in the proposed model. The model was tested on two cases (with current data, and with forecasted data) and solved using CPLEX 9.0 Solver.

Likewise, Feng and Long (2008) directed their effort to find a network layout that minimizes the total annual cost [58]. Interestingly and beside the annualized investment cost, pumping operating cost, and maintenance and amortization costs, cooling energy losses of pipes were regarded as one of the cost parameters in their objective function. A heuristic search technique was utilized in solving their developed mathematical model. Mainly, they adopted an improved form of GA, known as Single-parent GA. The problem setting put forward was constrained by three conditions. First, they enforced the common flow equilibrium constraint. Second, they imposed a maximum water velocity value to maintain system's hydraulic stability. Third and last, they implied a constraint on pipe diameter being an important factor in the design of a DCS. No other structural or technical constraints were taken into account. Also, no constraints were used to reflect the required service level; that is, demand and cooling temperature requirements. After running the model, their results proved that the developed algorithm can be of higher searching efficiency, while leading to reduced running and investment cost when compared to results obtained by using the shortest path approach.

Another study was conducted by the same authors two years later in the same area. In their following study, Feng and Long (2010) utilized standard GA while more constraints were incorporated in their model to make it more realistic as the previous one was overly simplified [40]. The additional constraints are (i) customer's cooling demand, (ii) pressure equilibrium constraints and, (iii) hydraulic stability constraints. Moreover, the objective function was slightly modified to include the initial investment cost, operational cost, and depreciation and maintenance costs only. The model was solved and tested using a case that serves both cooling and heating requirements of a set of 24 customers. The results showed that GA is an effective way to carry a global optimization of DCS design, yet does not guarantee an optimal solution.

Augusto et al. (2013) carried out a study to determine a network design criteria for DCS so that the total investment, maintenance and operational costs are minimized [3]. Prior to optimization, they utilized a sequential approach that included parameters identifications and simulation techniques to aid them in pipeline friction factor and system's hydraulic calculations. Two DC distribution schemes were under study, with and without secondary lines of which each of them included twelve ETSs with a total nominated cooling load of 24K-ton of refrigeration. The results of their optimization effort using an extensive search technique revealed results related to velocity limit at primary line, secondary line and plot take-off and pressure drop limits. Once these results were identified, pipe sizes were determined accordingly.

Clearly, only few studies addressed DCS optimization. These efforts, as discussed earlier, are summarized in Table 2.5.

Table 2.5: Summary of Optimization Efforts Addressing DC Networks

Study	**Objective Function**	**Constraints**		
		Structural	**Temperature**	**Pressure**
Chan et al. (2007)[31]	Minimize piping cost and pumping energy cost	✓		
Soderman (2007)[30]	Minimize running cost and annualized investment cost	✓		
Feng and Long (2008)[58]	Minimize annualized investment cost, pump operating cost, energy loss cost, and maintenance and amortization costs	✓		
Feng and Long (2010)[40]	Minimize annualized investment cost, pump operating cost, and maintenance and amortization costs	✓		✓
Khir [this work]	Minimize investment and operational costs	✓	✓	✓

2.6 Summary

To sum up, the general structural scheme of DCS follows the one observed in any DES. They share a structure that houses aggregated production plant (s), main distribution pipelines and energy transfer substations, of which each is customized to cater for a different purpose. A description of DCS's components and their related design consideration was highlighted in this chapter. As revealed, DCS and like other district systems have its own special design requirements. The uniqueness of DCS relies on its special technical consideration which strongly drives system's functionality and serviceability. To this end, special optimization models that are customized to DC settings are required and essential to reap the benefits of such application.

The reviewed literature showed that optimization-related efforts in the field of DCS are relatively scarce. Whether operating as stand-alone systems or in an integrated setting within a dual- or multi-purpose plant, limited attention was directed to the structural optimization of DC networks. This goes back to the fact that the applications of DCSs are relatively new, and thus, underdeveloped. From the few available related works, few key downsides were identified and summarized in what follows.

It was noticed that important technical considerations were overlooked in majority of proposed models. To the best of our knowledge, temperature- and pressure-related ones were absent in majority of the literature body. Given the fact that DCS is a service-oriented system, a well-defined service-level is crucial to ensure the right provision of cooling requirements in the right condition. Therefore, accommodating temperature-related condition is mandatory as customers are paying for getting the right and contracted cooling effect. Moreover and as the system involves movement of chilled water in pipelines, systems hydraulics are essential to ensure the continuous flow and delivery of service to the right customers and at the right time. More specifically, a DCS shall be designed and structured to withstand a maximum static pressure throughout the pipeline, while maintaining a critical pressure differential at each substation in the network. This can be captured only by identifying pressure-related behaviors of the system and reflecting them in forms of constraints.

Besides this, the majority of reviewed literature in the area of DCS structural optimization intended to reflect the optimization of one part of the system, being the piping configuration only without considering important network design aspects presented at both the upstream and downstream ends of the system. For instance, sizing the chiller plant is an important design parameter as the capacity produced by the plant drives the whole systems operations. In addition, the importance of ensuring a proper integration between the network and connected customer substations was not clearly evidenced in the reviewed published works. The latter can be reflected by imposing pressure-related constraints, as discussed earlier.

To stand out among the preceding few studies in the same area, we address the optimization of a DCS design while capturing structural constraints as well as both pressure- and temperature-related constraints, which are crucially responsible for systems functionality and integration with both the chiller plant and customers' ETS.

Chapter 3

Problem Setting and Description

This chapter presents the problem setting and formal description for the optimization of a DCS design while capturing structural aspects as well as both pressure- and temperature-related constraints in a holistic manner. Section 3.1 introduces the problem from a structural perspective. Sections 3.2 and 3.3 highlight the important technical parameters and constraints that govern system's functionality and its adherence to a certain service requirements.

3.1 Structural Aspects

We assume that a set of n customer buildings are to be connected to a single cooling source, denoted by r. The connection scheme is assumed to be indirect. This means that the customer cooling loads are to be supplied to the ETS installed at the individual customer's buildings and not directly to the building air handling units. The cooling demand for each customer building is assumed to be deterministic, periodic (with a one-day periodicity), and stationary (of which the peak daily data are used). For computational convenience, we assume that a day is divided into T time periods of equal duration (a period generally refers to one hour). We denote by τ the duration of every period $t \in T$. The demand for every customer $j \in C$ during every period $t \in T$ is denoted by d_j^t, and is expressed as a flow rate. A typical daily cooling load pattern is presented for illustration in Figure 3.1 below.

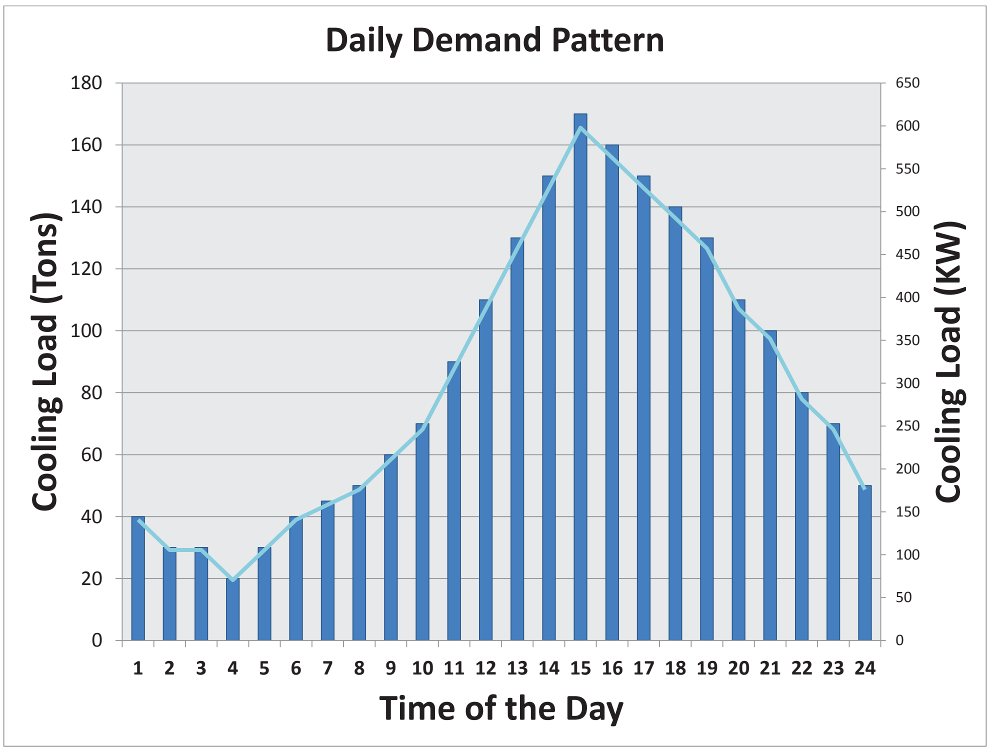

Figure 3.1: Typical Daily Cooling Demand Pattern

For modeling purposes, we assume that we are given an undirected graph $G = (V, E)$. The node set V includes three type of nodes: (i) a supply node, (ii) nodes representing customers' substations, and (iii) facultative nodes representing pipe junctions (henceforth called *Steiner nodes*). These latter nodes are optional and may be included in the network to reduce the total investment cost. The edge set E includes all potential links.

The overall piping network is assumed to take the form of a tree-like network. Hence, no loops/cycles are allowed. In other words, the network shall not accommodate any redundant pipes while ensuring connectivity. In our case, horizontal installations of pipes in underground trenches are assumed.

The supply node represents a single facility that includes a chiller plant and a TES (storage tank). The location of this facility is known and given. However, we need to determine the capacity of both production and storage systems. For that reason, a set of possible capacities is given for each of the chiller plant and storage tank based on market availability and demand needs. These sets are denoted by K and H, respectively. They are characterized by a fixed cost associated with building and installing them. FC_k^{plant} denotes the fixed cost associated with every chiller capacity k ($k \in K$). Similarly, FC_h^{tank} denotes the fixed cost associated with every tank capacity h ($h \in H$). In addition to this, there are variable costs for producing and storing a unit of chilled water during every period $t \in T$ and denoted by VC_t^{prod} and VC_t^{sto}; respectively.

An edge $e = \{i, j\} \in E$ represents a possible direct connection between nodes i and j. If an edge is selected to be part of the main distribution network, then it should be assigned a pipe type for installation out of a set M. For every pipe of type $m \in M$, we are given: (i) λ^m: a unit investment cost covering all expenses related to purchasing and installing a pipe; (ii) d^m: a pipe size (that is, inner diameter size); (iii) V_{min}^m: minimum allowable velocity, and (iv) V_{max}^m: maximum allowable velocity. These two latter characteristics enforce lower and upper bounds on the allowable flow rate of chilled water in every pipe type. We denote them by φ_m^{min} and φ_m^{min}, respectively.

Part of the problem is to find an optimal layout while sizing pipes for installation so that the investment cost is minimized. The cost parameter presenting this part of the problem is the fixed investment cost denoted by C_{ij}^m, which is a function of both pipe's unit cost λ^m and edge length l_{ij} (that is, $C_{ij}^m = \lambda^m \times l_{ij}$).

3.2 Hydraulic Aspects

A primary pumping scheme is assumed to be in use. Thus, the pumping head is located at the supply node and has the maximum pressure value in the system, denoted by p_{max}. Figure 3.2 below illustrates typical pressure-related changes exhibited in a DCS.

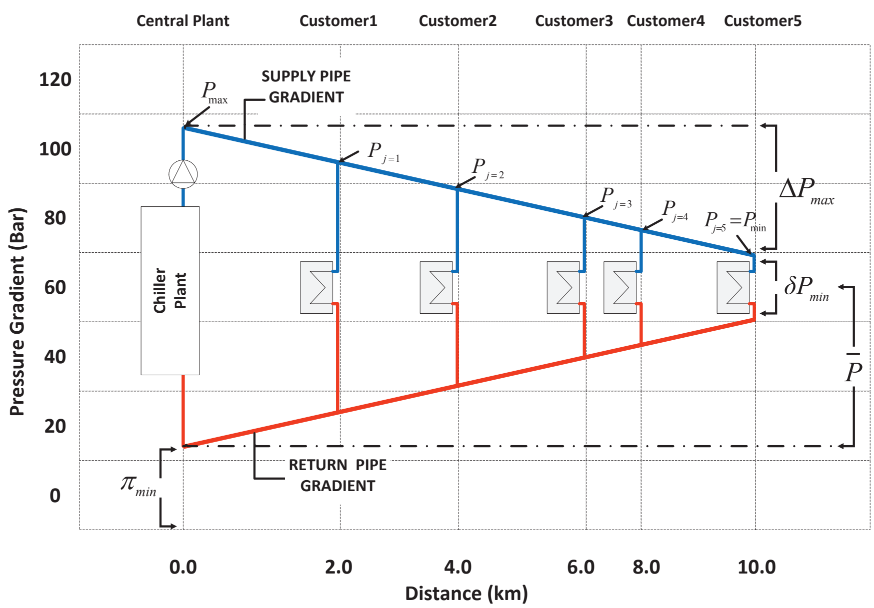

Figure 3.2: Sample Pressure Gradient for a Primary DC Distribution Network

Clearly and as the fluid moves down in the network, the pressure starts to drop due to fluid friction (major and minor losses). We denote by p_j the pressure value of incoming chilled water at any node $j \in V$. In addition, we denote by ΔP_{ij}^m the pressure drop along the edge that connects node i to node j when a pipe of size m is installed. More importantly, another differential pressure is experienced across customer's ETS and denoted by δP_j. This drop is encountered while customer's heat-exchangers extract needed energy before returning the chilled water through the return pipe. Such hydraulic-changes dictate maintaining certain values of pressure so that system's operations remain feasible.

Given that the pumping pressure is designed based on the pressure drop through the critical path [31], a maximum allowable pressure drop ΔP_{max} is defined to ensure delivery of chilled water to all customers. Likewise, a minimum allowable differential pressure δP_{min} is defined to ensure proper integration between customer's ETS and the main distribution network. Both parameters are considered in our model by imposing upper and lower bounds on pressure values at every node in the network. To this end, two main assumptions were made to mathematically represent pressure-related binding constraints. First, we assume that the chilled water pressure decreases linearly as it moves downstream in a path. Secondly, we assume that the technical and structural behaviours of the supply and return lines are symmetric. As can be seen from figure 3.3, the pumping pressure depends on both the mean pressure values along a path, denoted by $\bar{p}$, and a safety factor/cushion of which pressure cannot go below, denoted by π_{min}. In addition to this, the minimum pressure value in the system, denoted by p_{min} depends on two key parameters: (i) ΔP_{max}, and (ii) δP_{min}, as discussed earlier. Therefore, for any node $j \in V$:

- p_j shall not exceed a maximum pressure value p_{max}, known as pumping pressure and equals to $2\bar{p} - \pi_{min}$.
- p_j shall not drop below p_{min} which equals to the maximum value of $(\bar{p} + \frac{1}{2}\delta P_{min})$ and $(p_{max} - \Delta P_{max})$.

3.3 Thermal Aspects

Despite the fact that heat gains through the pipeline walls are reduced by means of coating them with insulation layers, it is impossible to prevent a temperature increase in the chilled water while being pumped and transported across the piping network. This is very important especially in places featuring hot weather and exhibiting a temperature difference between the transported water and its surrounding environment. More importantly, the temperature differential between supply and return water is a critical design factor due to the high costs associated with operating a small δT.

Figure 3.3 below illustrates possible change in chilled water temperature as it moves from the supply node to the successor nodes along each connected path. Moreover, the temperature differential constraining a DC network is shown as well.

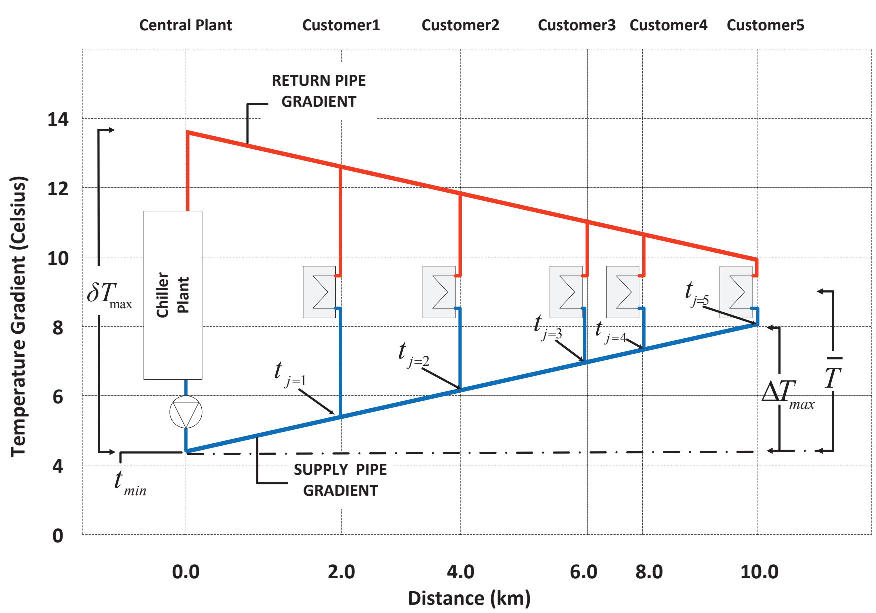

Figure 3.3: Sample Temperature Gradient for a Primary DC Distribution Network

We denote by t_{min} the minimum temperature value of the chilled water in the system, being situated at the supply node. Moreover, we denote by t_j the incoming temperature of chilled water at every node $j \in V$. As explained, experiencing heat gains in the system is possible and therefore can result in increasing the chilled water temperature while being transported. This encountered temperature increase is denoted by ΔT_{ij}^{m} and cumulative along the path that connects the supply node with every customer node $j \in C$ and should not exceed a preset threshold. This maximum temperature value is denoted by t_{max} and reflects the guaranteed maximum supply temperature as contracted with all customers. It is also controlled by the system return temperature that is needed to maintain a certain value for temperature differentials (denoted by δT_j) as discussed earlier in Section 2.3.2. Therefore, and following the same principle used to define pressure limits, temperature limits are defined for any node $j \in V$.

3.4 Scope of the Problem

Our main focus is to develop and validate a comprehensive model which explicitly captures the practical features of the system, especially the ones that play vital role in determining the optimal network structure and operations as highlighted above. More precisely, our objective is to minimize the total investment and operational costs by determining:

1. The capacity to be installed at the chiller plant and storage tank.
2. The layout of the main distribution network as well as the sizing of each pipe in the network.
3. The quantities of chilled water to be produced and stored at each period of time.

Chapter 4

Problem Formulation

Given the above description, one can notice that the problem can be decomposed into two related subproblems:

- subproblem 1 addresses decisions related to the design and operations of the chiller plant and storage tank.
- subproblem 2 addresses decisions related to the design of the main distribution network.

Even though these two subproblems are related in the sense that both designs are essentially dependent on cooling demand and not on each other, the network design is influenced by the quantity to be delivered to each customer at every period of time, and not on the quantities produced or stored. Regardless its original source (direct production or stored quantities), the required cooling loads will be only transported via the distribution network. Similarly, the sizing of plant and tank depends on the quantities demanded by customers and not on the network topology or its pipes size. Hence, both problems could be addressed and solved independently. In the sequel, we shall present two MIP models for these two problems as follows.

4.1 A Model for Optimal Plant Design and Operation

4.1.1 Decision Variables

We introduce the following decision variables:

- y_k: binary variable that takes value 1 if plant is built and installed at its k^{th} capacity, and 0 otherwise, $k \in K$.

- g_h: binary variable that takes value 1 if storage tank is built and installed at its h^{th} capacity, and 0 otherwise, $h \in H$.

- F_t: amount of chilled water produced by chiller plant during period t, $t \in T$, expressed as flow rate.

- I_t: stock level in storage tank at the end of period t, $t \in T$.

4.1.2 A Mixed-Integer Linear Programming (MILP) Formulation

Using these variables, a valid formulation for the Plant Design and Operation (PDO) problem is presented in the following:

$$\text{Minimize} \sum_{k \in K} FC_k^{plant} y_k + \sum_{h \in H} FC_h^{tank} g_h + \sum_{t \in T} VC_t^{prod} F_t + \sum_{t \in T} VC_t^{Sto} I_t \quad (4.1)$$

subject to:

$$\sum_{k \in K} y_k = 1, \quad (4.2)$$

$$\sum_{h \in H} g_h \leq 1, \tag{4.3}$$

$$F_t \leq \sum_{k \in K} Q_k y_k, \qquad t \in T, \tag{4.4}$$

$$I_t \leq \sum_{h \in H} D_h g_h, \qquad t \in T, \tag{4.5}$$

$$I_{t-1} + \tau F_t = I_t + \tau \sum_{j=1}^{n} d_j^t, \qquad t \in T, \tag{4.6}$$

$$I_o = I_T, \tag{4.7}$$

$$F_t, I_t \geq 0, \qquad t \in T, \tag{4.8}$$

$$y_k, g_h \in \{0, 1\}, \qquad k \in K, h \in H. \tag{4.9}$$

The objective function (4.1) minimizes the sum of the fixed costs of building chiller plant and storage tank along with the variable production and storage costs. Constraint (4.2) ensures that only one capacity is selected for chiller plant installation. Constraint (4.3) indicates that the installation of a Storage tank is optional, and is assigned at most one capacity. Constraint (4.4) ensures that the produced amount of chilled water does not exceed the installed capacity of the chiller plant. Likewise, constraint (4.5) ensures that the amount of stored chilled water does not exceed the installed storage tank capacity. Constraint (4.6) imposes the balance constraints for the storage tank. Constraint (4.7) reflects modeling the steady state; hence, the transient state that occurs when we start operating the plant for the first time is not considered. Constraints (4.8) and (4.9) define the non-negative and binary variables, respectively.

4.2 A Model for Optimal Network Design

Now, we turn our attention to the optimization of the distribution network. Given the input undirected graph $G = (V, E)$, we define a bi-directed digraph by replacing each edge $e = \{i, j\} \in E$ with two arcs (i, j) and (j, i) with opposite directions. We denote by A the set of arcs, V_j^- the set of predecessor nodes to node j, and V_j^+ the set of successor nodes to node j. Furthermore, we denote by C the set of customer nodes, S the set of Steiner nodes, and r the facility node.

4.2.1 Decision Variables

- z_{ij}**:** binary variable that takes value 1 if arc (i, j) is selected, and 0 otherwise, $(i, j) \in A$.

- x_{ij}^m**:** binary variable that takes value 1 if pipe of type m is installed on arc (i, j), and 0 otherwise, $m \in M$, $(i, j) \in A$.

- f_{ij}^{tm}**:** amount of flow rate in arc (i, j) during period t if pipe of type m is selected for installation on this arc, $(i, j) \in A$, $m \in M$, $t \in T$.

- t_j**:** temperature of supplied chilled water to node j, $j \in V$.

- p_j**:** pressure of supplied chilled water to node j, $j \in V$.

4.2.2 A Mixed-Integer Nonlinear Programming (MINLP) Formulation

A valid formulation of the network design problem is presented in what follows.

$$\text{Minimize} \sum_{(i,j)\in A} \sum_{m\in M} c_{ij}^m x_{ij}^m \tag{4.10}$$

subject to:

$$\sum_{i\in V_j^-} z_{ij} = 1, \qquad \forall j \in C, \tag{4.11}$$

$$\sum_{i\in V_j^-} z_{ij} \leq 1, \qquad \forall j \in S, \tag{4.12}$$

$$\sum_{m\in M} x_{ij}^m = z_{ij}, \qquad \forall (i,j) \in A, \tag{4.13}$$

$$\sum_{i\in V_j^-} \sum_{m\in M} f_{ij}^{tm} - \sum_{k\in V_j^+} \sum_{m\in M} f_{jk}^{tm} = d_j^t, \qquad \forall j \in C, t \in T \tag{4.14}$$

$$\sum_{i\in V_j^-} \sum_{m\in M} f_{ij}^{tm} = \sum_{k\in V_j^+} \sum_{m\in M} f_{jk}^{tm}, \qquad \forall j \in S, t \in T \tag{4.15}$$

$$\varphi_m^{min} x_{ij}^m \leq f_{ij}^{tm} \leq \varphi_m^{max} x_{ij}^m, \qquad \forall (i,j) \in A, m \in M, t \in T \tag{4.16}$$

$$t_j z_{ij} = t_i z_{ij} + \sum_{m\in M} \Delta T_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A, \tag{4.17}$$

$$t_{min} \leq t_j \leq t_{max} \qquad \forall j \in C, \tag{4.18}$$

$$t_{min} \sum_{i \in V_j^-} z_{ij} \leq t_j \leq t_{max} \sum_{i \in V_j^-} z_{ij} \qquad \forall j \in S, \tag{4.19}$$

$$t_r = t_{min}, \tag{4.20}$$

$$p_j z_{ij} = p_i z_{ij} - \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A, \tag{4.21}$$

$$p_{min} \leq p_j \leq p_{max} \qquad \forall j \in C, \tag{4.22}$$

$$p_{min} \sum_{i \in V_j^-} z_{ij} \leq p_j \leq p_{max} \sum_{i \in V_j^-} z_{ij} \qquad \forall j \in S, \tag{4.23}$$

$$p_r = p_{max}, \tag{4.24}$$

$$x_{ij}^m, z_{ij}, \in \{0,1\}, \qquad \forall (i,j) \in A, m \in M, \tag{4.25}$$

$$f_{ij}^{tm}, \geq 0 \qquad \forall (i,j) \in A, t \in T, m \in M, \tag{4.26}$$

$$t_j, p_j \geq 0 \qquad \forall j \in C \cup S. \tag{4.27}$$

In this formulation, the objective (4.10) is to minimize fixed costs associated with purchasing and installing distribution pipes. Constraints (4.11)-(4.12) enforce the connectivity (as well as the non redundancy) of the network. They indicate that each customer node has exactly one incoming arc, and each Steiner node has at most one incoming arc; respectively. Since x is a binary variable, then by virtue of (4.11) and (4.12), z is necessarily a binary variable and the integrality of the z-variables is relaxed to $z \geq 0$.

Constraints (4.13) are introduced to ensure that only one pipe type is installed at any arc. Constraints (4.14)-(4.15) are the flow conservation conditions which must hold for all non-root nodes. Note that Constraints (4.14) hold only for customer nodes. At these nodes, part of the flow shall be delivered to satisfy cooling requirement, remaining flow (if any) shall be transported to the downstream node in the network. This is not applicable for Steiner nodes as these nodes are only pipe junction nodes with no cooling requirements, as expressed in (4.15). Constraint (4.16) represents flow capacity constraints. They enforce the logical relationship between the x- and f-variables (that is, if $x_{ij}^m = 1$, then f_{ij}^{tm} shall take any value in $[\varphi_m^{min}, \varphi_m^{max}]$, otherwise $f_{ij}^{tm} = 0 \; \forall (i,j) \in A, m \in M, t \in T$).

The combination of Constraints (4.17)-(4.20) ensure that supplied temperature of chilled water to all customer nodes and selected Steiner nodes is not exceeding the contractual/desired supply temperature. Similarly, Constraints (4.21)-(4.24) guarantee that both pressure drop through pipes and across customer substation are not exceeded and within the allowable limits. Finally, Constraints (4.25)-(4.27) represent non-negativity and integrality conditions.

4.2.3 Valid Inequalities

It is possible to further enhance the model representation by appending the following valid inequalities. These constraints emphasize explicitly that the resulted graph is a directed, acyclic and connected graph.

$$z_{ij} + z_{ji} \leq 1, \qquad \forall (i,j) \in A, \tag{4.28}$$

$$z_{jk} \leq \sum_{i \in V_j^-} z_{ij}, \qquad \forall j \in S, \quad \forall k \in V_j^+, \tag{4.29}$$

$$\sum_{i \in V_j^-} z_{ij} \leq \sum_{k \in V_j^+} z_{jk}, \qquad \forall j \in S. \tag{4.30}$$

Constraint (4.28) is usually called the two-node subtour elimination constraint. It indicates that the resulting subgraph cannot include two arcs of opposite directions. Constraints (4.29) and (4.30) assert special connectivity rules on Steiner nodes due to their facultative nature. Both constraints are in the form of conditional constraints. Constraint (4.29) indicates that no outgoing arc from any Steiner node shall be included in the network if there is no incoming arc to this node. Similarly, Constraint (4.30) ensures that at least one outgoing arc shall be included if there is one incoming arc.

4.2.4 Model Linearization

As observed, the model is composed of equation's (4.10) to (4.30), and contains a couple of nonlinear inequalities (namely, (4.17) and (4.21)). For that reason, we utilize the Reformulation-Linearization Technique (RLT) proposed by Sherali and Adams ([59] [60] [61]) to derive an equivalent linear representation of the model. In this section, we present the RLT two essential steps, (i) reformulation phase and, (ii) linearization phase.

Reformulation phase: we append certain additional implied polynomial constraints to the problem. This is accomplished using the following steps:

1. Using (4.11), we construct the following equalities:

$$\left[\sum_{i \in V_j^-} z_{ij} = 1 \right] \times t_j, \qquad \forall j \in C, \tag{4.31}$$

$$\left[\sum_{i \in V_j^-} z_{ij} = 1\right] \times p_j, \qquad \forall j \in C, \tag{4.32}$$

2. Similarly, using (4.12), we construct the following inequalities:

$$\left[\sum_{i \in V_j^-} z_{ij} \leq 1\right] \times t_j, \qquad \forall j \in S, \tag{4.33}$$

$$\left[\sum_{i \in V_j^-} z_{ij} \leq 1\right] \times p_j, \qquad \forall j \in S, \tag{4.34}$$

3. In light of both (4.18) and (4.19), the following valid inequality can be derived.

$$\left[t_{min} \sum_{i \in V_j^-} z_{ij} \leq t_j \leq t_{max} \sum_{i \in V_j^-} z_{ij}\right] \times z_{ij} \qquad \forall j \in S, \tag{4.35}$$

4. Similarly, using constraints (4.22) and (4.23), the following inequality are valid.

$$\left[p_{min} \sum_{i \in V_j^-} z_{ij} \leq p_j \leq p_{max} \sum_{i \in V_j^-} z_{ij}\right] \times z_{ij} \qquad \forall j \in S, \tag{4.36}$$

5. From Constraints (4.20) and (4.24); respectively, we construct the following valid equalities.

$$[t_r = t_{min}] \times z_{rj}, \tag{4.37}$$

$$[p_r = p_{max}] \times z_{rj}, \tag{4.38}$$

6. From (4.28), we construct the following valid inequalities:

$$[1 - z_{ij} - z_{ji} \leq 0] \times t_j, \qquad \forall (i,j) \in A, \tag{4.39}$$

$$[1 - z_{ij} - z_{ji} \leq 0] \times p_j, \qquad \forall (i,j) \in A, \tag{4.40}$$

7. The product of constraint (4.28) by the bound-factors in (4.18) and (4.22) yields to:

$$[1 - z_{ij} - z_{ji} \leq 0] \times (t_{max} - t_j), \qquad \forall (i,j) \in A, \tag{4.41}$$

$$[1 - z_{ij} - z_{ji} \leq 0] \times (p_{max} - p_j), \qquad \forall (i,j) \in A, \tag{4.42}$$

8. Using (4.29), the following inequalities are valid:

$$\left[z_{jk} \leq \sum_{i \in V_j^-} z_{ij} \right] \times t_j, \qquad \forall j \in S, \quad \forall k \in V_j^+, \tag{4.43}$$

$$\left[z_{jk} \leq \sum_{i \in V_j^-} z_{ij} \right] \times p_j, \qquad \forall j \in S, \quad \forall k \in V_j^+, \tag{4.44}$$

9. From constraint (4.30), we construct the following valid inequalities.

$$\left[\sum_{i \in V_j^-} z_{ij} \leq \sum_{k \in V_j^+} z_{jk} \right] \times t_j, \qquad \forall j \in S. \tag{4.45}$$

$$\left[\sum_{i \in V_j^-} z_{ij} \leq \sum_{k \in V_j^+} z_{jk} \right] \times t_j, \qquad \forall j \in S. \tag{4.46}$$

Linearization phase: we introduce two new RLT variables to linearize constraints (4.17), (4.21), and (4.31) - (4.46). Towards this end, we define

$$u_{ij} = t_i z_{ij} \qquad \forall j \in V, \quad \forall (i,j) \in A, \tag{4.47}$$

and

$$w_{ij} = p_i z_{ij} \qquad \forall j \in V, \quad \forall (i,j) \in A. \tag{4.48}$$

Furthermore, we derive the following identities from (4.21) and (4.25) for linearizing $t_j x_{ij}^{tm}$ and $p_j x_{ij}^{tm}$; respectively.

$$t_j z_{ij} = u_{ij} + \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A, \tag{4.49}$$

$$p_j z_{ij} = w_{ij} - \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A, \tag{4.50}$$

After this, we replace each product term in (4.31) - (4.46) by its corresponding single variable from (4.47) - (4.50). Hence, forming below linearized constraints.

$$\sum_{i \in V_j^-} u_{ij} + \sum_{i \in V_j^-} \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m = t_j \qquad \forall j \in C, \tag{4.51}$$

$$\sum_{i \in V_j^-} w_{ij} - \sum_{i \in V_j^-} \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m = p_j \qquad \forall j \in C, \tag{4.52}$$

$$\sum_{i \in V_j^-} u_{ij} + \sum_{i \in V_j^-} \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m \leq t_j \qquad \forall j \in S, \tag{4.53}$$

$$\sum_{i \in V_j^-} w_{ij} - \sum_{i \in V_j^-} \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m \leq p_j \qquad \forall j \in S, \tag{4.54}$$

$$u_{ij} + u_{ji} \leq t_j - \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A, \tag{4.55}$$

$$u_{ij} + u_{ji} \geq t_j - t_{max} + t_{max} z_{ij} - \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m + t_{max} z_{ji} \qquad \forall (i,j) \in A, \tag{4.56}$$

$$u_{jk} \leq \sum_{i \in V_j^-} u_{ij} + \sum_{i \in V_j^-} \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m \qquad \forall j \in S, \quad \forall k \in V_j^+, \tag{4.57}$$

$$\sum_{i \in V_j^-} u_{ij} + \sum_{i \in V_j^-} \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m \leq \sum_{k \in V_j^+} u_{jk} \qquad \forall j \in S, \tag{4.58}$$

$$t_{min} z_{ij} \leq u_{ij} \leq t_{max} z_{ij} \qquad \forall (i,j) \in A, \tag{4.59}$$

$$w_{ij} + w_{ji} \leq p_j + \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A, \tag{4.60}$$

$$w_{ij} + w_{ji} \geq p_j - p_{max} + p_{max} z_{ij} + \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m + p_{max} z_{ji} \qquad \forall (i,j) \in A, \tag{4.61}$$

$$w_{jk} \leq \sum_{i \in V_j^-} w_{ij} - \sum_{i \in V_j^-} \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m \qquad \forall j \in S, k \in V_j^+, \tag{4.62}$$

$$\sum_{i \in V_j^-} w_{ij} - \sum_{i \in V_j^-} \sum_{m \in M} \Delta P_{ij}^m x_{ij}^m \leq \sum_{k \in V_j^+} w_{jk} j \in S, \tag{4.63}$$

$$p_{min}z_{ij} \leq w_{ij} \leq p_{max}z_{ij} \qquad \forall (i,j) \in A, \tag{4.64}$$

$$u_{rj} = t_{min}z_{rj} \qquad \forall j \in V_r^+, \tag{4.65}$$

$$w_{rj} = p_{max}z_{rj} \qquad \forall j \in V_r^+, \tag{4.66}$$

Finally, the resulting **Network Design (ND) model** is a MILP model and is composed of **(4.10)-(4.16), (4.18)-(4.20), (4.22)-(4.27), and (4.51)-(4.66).**

Chapter 5

Computational Experiments

In this chapter, we present the results of a computational study that aims at demonstrating the practical usefulness of the proposed models. The proposed MILP models were coded, and then implemented and tested on instances of various sizes with the aid of an optimization software package; namely, IBM ILOG CPLEX 12.5. These numerical tests were guided by three objectives:

- To test and validate the solvability of the proposed models.
- To examine their performance when generating optimal solutions and compare it against running them using heuristics to generate feasible/near optimal solutions.
- To study the impact of changing certain problem parameters on the performance of solving the proposed models to optimality (such as network size, peak cooling loads and number of time periods).

Firstly, a brief description on data used to test and run the proposed models is given. Then, the result of examining each of the above mentioned objectives is presented.

5.1 Description of the Problem Instances

In an effort to test the model on realistic cases, the two and only DC utilities in Qatar were approached to help feeds the model using real-life data. Moreover, an overseas company was approached for the same purpose. Unluckily, all our attempts to get these real-life instances were fallen short as collaborated companies refused to share the full set of requested data due to their sensitivity and confidentiality as responded. Notwithstanding this limitation, we created our set of testing data with the aid of literature and consultation with respective experts in the field of DCS. This will guarantee generating hypothetical instances while incorporating the full sense of what is realistic and what is not.

Three classes of the problem were generated, in which each corresponds to a different network size. In our case, the size reflects the number of nodes that make up a network; thus, generated problems cover small, medium and large scale networks. Table 5.1 below illustrate the key characteristics attributed to every problem class.

Table 5.1: Characteristics of the Problem Classes

	Number of		
Problem	**Customer Nodes (C)**	**Steiner Nodes (S)**	**Periods (T)**
Class 1	10	5	4
Class 2	20	10	6
Class 3	40	20	8

For each problem class, five instances were generated by varying the total cooling demands required during the peak hour (period). Table 5.2 below illustrates the key characteristics attributed to every subclass.

The detailed set of the created data to run each of the instances is presented in the Appendix.

Table 5.2: Characteristics of the Problem Subclasses

Subclass	Peak Cooling Load (TR)
1	10000
2	20000
3	40000
4	80000
5	100000

Table 5.3 below gives an overview of the number of variables and constraints in models (PDO) and (ND) for each of the problem classes.

Table 5.3: Size of the Problem Instances

Problem	No. of Variables		No. of Constraints	
	PDO	ND	PDO	ND
Class 1	29	6755	15	6646
Class 2	33	22067	21	20744
Class 3	37	64092	27	47722

5.2 Performance of Solving MILP Formulations to Optimality

In this section, we present the results that we have obtained after solving the developed instances optimally using IBM ILOG CPLEX 12.5 on a Intel(R) Core(TM) i7-3520M CPU @ 2.90 GHz with 4.00 GB RAM.

The CPU time required to solve each of these instances is given in Table 5.4.

Additionally, results are reported for each class as shown in Table 5.5. These reported results include mean, minimum and maximum CPU time required for solving each of the proposed models (computed over all solved instances in each class).

Table 5.4: CPU Time for Solving POD and ND Models to Optimality for Every Instance

	PDO Model	ND Model
Instance	**CPU (s)**	**CPU (min)**
1.1	1.74	0.14
1.2	0.87	0.29
1.3	1.12	0.26
1.4	0.92	0.16
1.5	0.99	0.15
2.1	1.1	6.83
2.2	1.09	21.87
2.3	0.92	16.90
2.4	0.98	23.24
2.5	1.12	15.18
3.1	1.03	14.49
3.2	1.06	42.09
3.3	0.96	142.95
3.4	0.93	378.88
3.5	1.07	750.31
Avg.	1.06	94.25

Table 5.5: CPU Time for Solving POD and ND Models to Optimality for Every Class

Class	$\|V\|$	$\|C\|$	$\|S\|$	$\|T\|$	**PDO Model CPU (s)**			**ND Model CPU (min)**		
					Avg.	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**
Class 1	15	10	5	4	1.13	0.87	1.74	0.2	0.1	0.3
Class 2	30	20	10	6	1.04	0.92	1.12	16.8	6.8	23.2
Class 3	60	40	20	8	1.01	0.93	1.07	201.7	14.5	750.3

As noticed, an optimal solution can be generated within seconds for the proposed PDO model, and within 1 hour and 30 minutes on average for the proposed ND model. It is also noticed that the largest class of instances, with 60 nodes, requires on average 3 hours and 20 minutes to be solved optimally. It is also observed that instance No. 3.5 took 12 hours and 30 minutes to be solved, which is relatively a long time. For that reason, the performance of solving the ND formulation using MIP-based heuristics is investigated in the following section.

5.3 Performance of Solving MILP Formulations Using MIP-based Heuristics

In this section, stopping criteria other than optimality were utilized through the use of different heuristics. These solution techniques were only applied on the ND model as the CPU time needed to solve the PDO model to optimality was considerably short. Therefore, performance of the ND model has been tested and cross compared between different solution methods. The used MIP-based heuristics are:

- Generating multiple solutions by invoking "populate" procedure. Thus, optimality is not the stopping criterion any more. Rather, we are using a populate limit by specifying the size of solution pool, that is, the number of solutions to be generated before the populate procedure stops. In our case, we are limiting the solution pool to 5, 10 and 15 solutions.
- Setting an optimality tolerance of 1%, 2% and 5%, respectively.
- Setting a time limit up to one hour.

The obtained results from each of these heuristics are presented in the following subsections separately. Then, a summary of performance comparison is presented.

5.3.1 Invoking Populate

The performance of ND model in generating a set of solutions by populating the solution pool is tested in this section. The "populate" procedures were invoked while limiting the number of solutions generated for the solution pool to 5, 10 and 15 solutions. The CPU time, and percent deviation from the optimal solution (based on the best obtained solution from the solution pool) are recorded and presented in table 5.6 below.

Table 5.6: Performance of Solving ND model by Invoking Populate

					CPU (s)			GAP %		
Class	$\|V\|$	$\|C\|$	$\|S\|$	$\|T\|$	Solution Pool					
					5	10	15	5	10	15
Class 1	15	10	5	4	3.67	8.15	16.05	12.12%	1.87%	0.00%
Class 2	30	20	10	6	35.97	966.50	1754.23	26.93%	3.06%	0.06%
Class 3	60	40	20	8	1509.40	14429.13	17000.10	21.81%	6.48%	3.16%

5.3.2 Setting a Tolerance

In what follows, the performance of ND model in generating a solution within 1%, 2% and 5% tolerance is presented. This mainly includes reporting the average CPU time, and the percent deviation from the optimality as shown in table 5.7

Table 5.7: Performance of Solving ND Model by Setting Tolerance

					CPU (s)			GAP %		
Class	$\|V\|$	$\|C\|$	$\|S\|$	$\|T\|$	Tolerances					
					1%	2%	5%	1%	2%	5%
Class 1	15	10	5	4	11.388	10.706	8.694	0.00%	0.29%	0.81%
Class 2	30	20	10	6	977.882	856.622	561.414	0.00%	0.49%	1.12%
Class 3	60	40	20	8	10084.006	9500.702	8287.934	0.15%	0.63%	2.26%

5.3.3 Setting a Time Limit

In here, the CPU time limit was set to one hour (3600 seconds) for every run, while keeping the default parameters in CPLEX 12.1 unchanged. The obtained results were compared with the optimal solution results and reported in table 5.8 below.

Table 5.8: Performance of Solving ND Model within One Hour

Class	$\|V\|$	$\|C\|$	$\|S\|$	$\|T\|$	**GAP%**
Class 1	15	10	5	4	0.00%
Class 2	30	20	10	6	0.00%
Class 3	60	40	20	8	2.64%

5.4 Performance Comparison Between all the Used Heuristics and the Optimality

This section gives a comparison summary between the relative performances of the above discussed MIP-based heuristics in reference to performance of solving ND model to optimality. Two performance measures are presented, namely, the relative CPU time and the relative MIP-GAP. A summary of performance comparison is presented in Table 5.9.

Table 5.9: Relative Performance Comparison of Solving ND Model Using MIP-based Heuristics

		Pool Size			Tolerance		
		5	**10**	**15**	**1%**	**2%**	**5%**
Class 1	**%Change in CPU**	-69	-31	35	-4	-10	-27
	%GAP	12.12	1.87	0.00	0.00	0.29	0.81
Class 2	**%Change in CPU**	-96	-4	74	-3	-15	-44
	%GAP	26.93	3.06	0.06	0.00	0.49	1.12
Class 3	**%Change in CPU**	-91	-9	7	-37	-40	-48
	%GAP	21.81	6.48	3.16	0.15	0.63	2.26
AVG	**%Change in CPU**	-85	-15	39	-15	-22	-40
	%GAP	20.29	3.80	1.07	0.05	0.47	1.40

It is clear that among the presented heuristics, the tolerance strategy appears more attractive. We see from this table, that if a 5%-optimality tolerance is set, then significant reduction of the CPU time is achieved (by 40% on average), while the proposed solution exhibit a reduced optimality gap that is often less that 1.5%.

It is worth noting that since the problem is NP-hard problem, the computational effort needed to solve large scale instances becomes very large. To address such problems, the development of more enhanced mathematical models (E.g. branch-and-cut, branch-and-price) and/or meta-heuristic methods may be useful.

5.5 Sensitivity Analysis

The computation time required to solve the various instances varies from one class to another (as illustrated earlier in Section 5.2). Similarly, it differs within the class itself, that is, between subclass instances. To this end, we attempt to test the impact of changing some of the key parameters on the performance of the proposed models. In this section, we limit our sensitivity analysis to include: (i) peak cooling load; and (ii) number of time periods of which the demand is known for each customer.

5.5.1 Impact of Changing Peak Cooling Load

Within each class of instances, the impact of varying the peak cooling load on both PDO and ND models' performance was tested. Following the characteristics of problem classes illustrated earlier in Table 5.1, Figures 5.1 and 5.2 illustrate how CPU time changes when changing the peak load demand in every problem class when solving PDO and ND models, respectively.

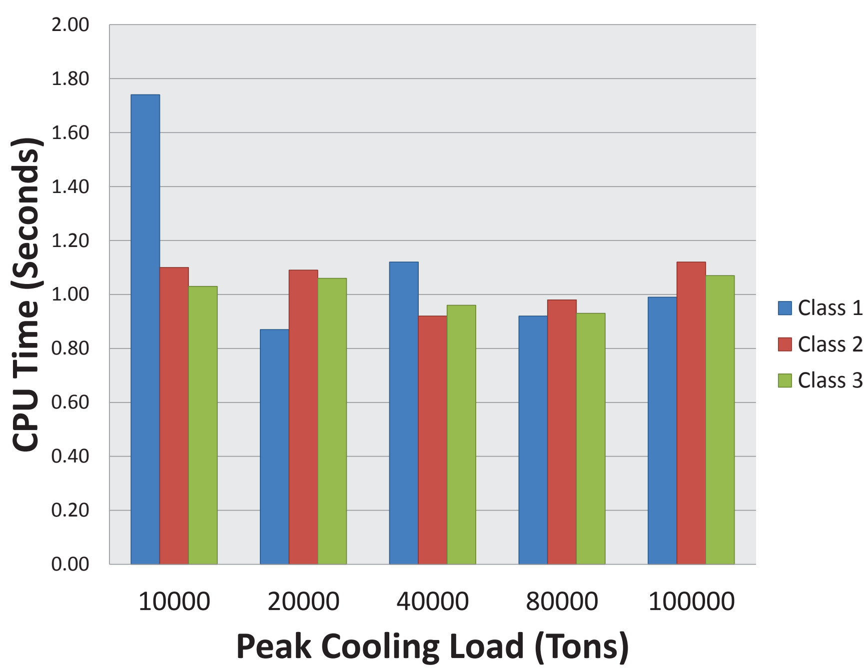

Figure 5.1: Impact of Changing Peak Cooling Load on the Performance of PDO Model

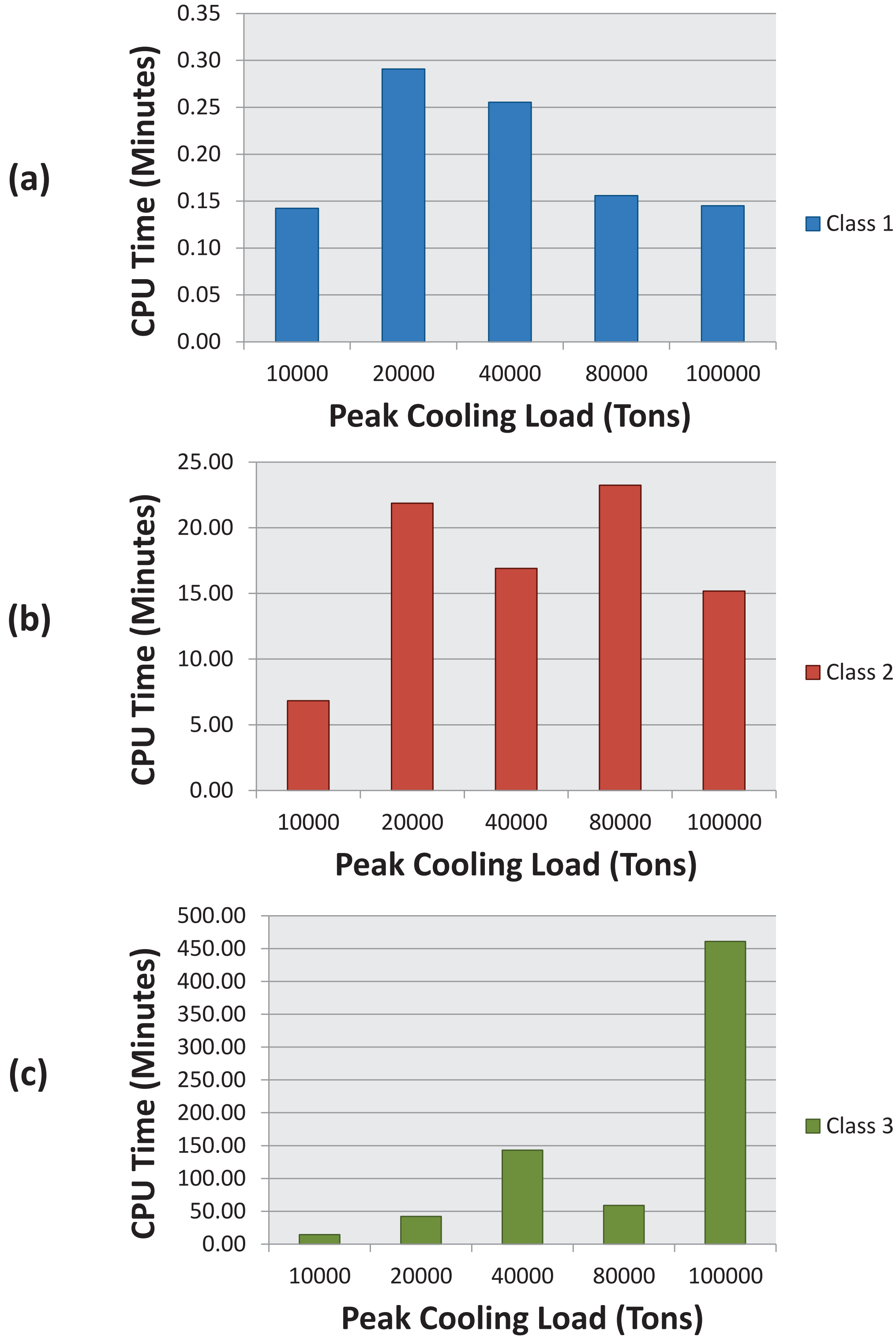

Figure 5.2: Impact of Changing Peak Cooling Load on the Performance of ND Model

As shown and in the PDO model, no significant difference was observed in regard to CPU times within each class. This can be explained by the fact that solutions in these models are obtained within a very short time (within seconds). On the other hand, an irregular behavior was noticed when it comes to the ND model. To this end and as observed, we can initially conclude the following while bearing in mind that more extensive testing is required to generate more rigid conclusions:

- The performance of PDO model is insensitive to the value of peak cooling load.
- The performance of ND model is sensitive to the value of peak cooling load, but no trend was observed.

5.5.2 Impact of Changing Number of Time Periods

Given the dynamic nature of a DCS, the number of time periods of which the demand is known for each customer presents an important design parameter especially when sizing plant and dimensioning pipes. In here, we limit the impact test of changing T on the performance of ND Model only as the CPU time needed to solve the PDO model to optimality was found to be considerably short. Seven different instances were tested by considering 4, 6, 8, 12 and 24 periods. The impact of this change on the CPU time is illustrated in Figure 5.3 below.

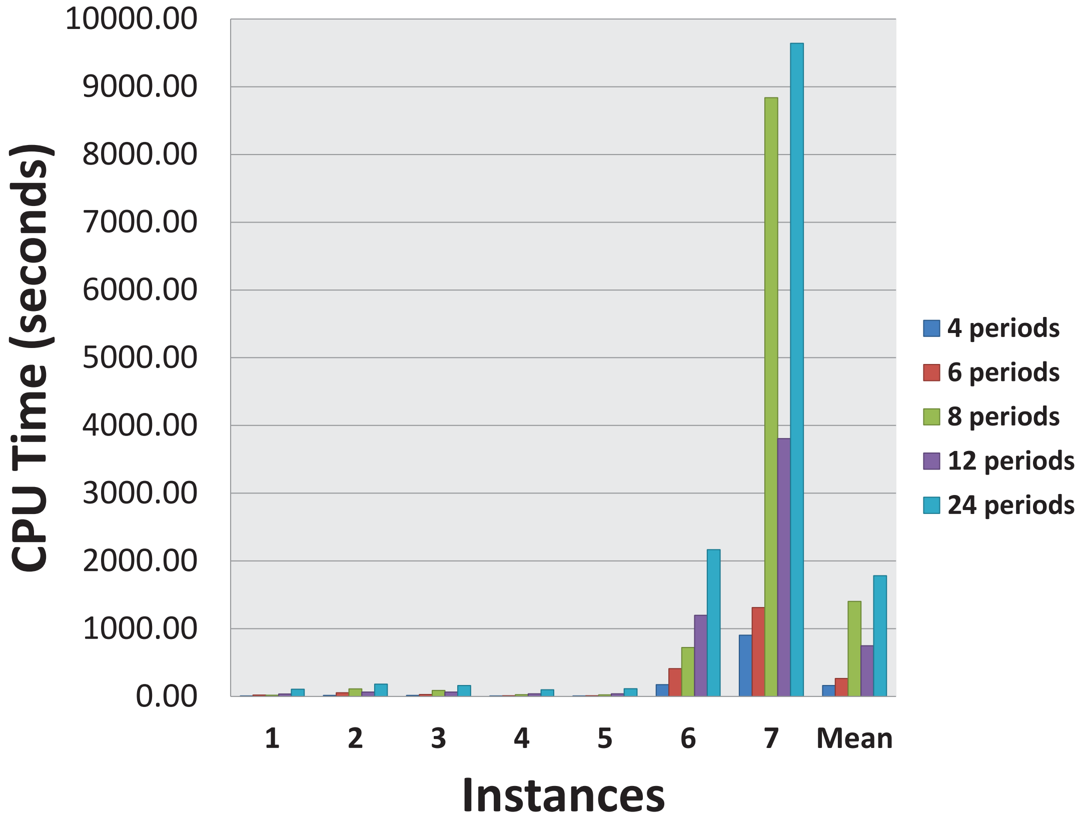

Figure 5.3: Impact of Changing the Number of Periods on the Performance of ND Model

By first glance this figure, it can be noticed that there is a positive correlation between the time needed to solve an instance optimally and the number of periods considered in almost all the tested cases. In other words, the more number of design periods we incorporate, the more CPU time it takes to reach optimality. More analysis are required to further verify this observed trend.

Chapter 6

Conclusion and Future Research

The inherent benefits of a DCS when adopted under right conditions and settings cannot be overstated. By being the least localized cooling option with the ability to bring in cost and environmental advantages, a DCS stands as a more attractive alternative when compared with the other conventional cooling schemes. To capitalize on such benefits, a proper planning is undoubtedly required. The significant initial investment cost required to build a DCS prompts having sound and more ideally, optimal, decisions to reap as much benefits as possible. In view of this, this research aims at developing MILP models that aid in making decisions related to chiller plant capacity, storage tank capacity, distribution network size and configuration, and quantities to be produced and stored during every period of time. Unprecedentedly, proposed models were built to capture and reflect constraints related to the unique practical characteristics of DCSs presented in both structural and technical sides. More specifically and unlike the previous efforts devoted in this area, models were built to include both thermal and hydraulic characteristics of the system. This was done by incorporating temperature- and pressure- related constraints. Developed models were then coded and tested using a commercial solver. More importantly, computational experiments proved the solvability of developed models to optimality within reasonable CPU time.

In conclusion, the presented research contributes in further strengthening the optimization efforts exhibited in the field of DCS. More essentially, it is hoped that this work will help engineers to better design minimum cost DC networks, in a more efficient, effective, and operationally-feasible manner. This research also provides a sensible ground for future research in the same area. Prospect works can build upon the current models by pursuing improvements or extensions, both scope and/or performance wise. This can include incorporating more decisions related to plants' operation, sizing of its' equipment, inclusion and location of booster pumps in large networks, and/or considering multiple plants serving a district. Moreover, models can be reformulated to consider looped or hybrid schemes, instead of the assumed tree-like structure.

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Appendix

Data Sets for Models Testing and Validation

This appendix contains the detailed data used to run each class and instance.

Network Related Data for **Class 1**

Set of possible chiller plant capacities		
k	**Capacity (TR)**	**Fixed Cost (QAR)**
1	5000	54750000
2	8000	87600000
3	10000	120450000
4	18000	183960000
5	25000	189617500
6	30000	224256000
7	40000	292438000
8	60000	438657000
9	75000	548321250
10	80000	584876000
11	100000	731095000

Set of possible storage tank capacities		
h	**Capacity (TR)**	**Fixed Cost (QAR)**
1	2000	6000000
2	4000	12000000
3	8000	24000000
4	12000	36000000
5	16000	48000000
6	20000	60000000
7	25000	75000000
8	30000	90000000
9	40000	120000000

Variable production and storage cost		
Periods (t)	**Variable Cost (QAR)**	
	Production	**Storage**
1	35	20
2	40	20
3	50	20
4	30	20

Pressure-related data (100kPa)	
Supply pressure from plant	12.8
Return pressure to plant	1.5
Minimum pressure differential at ETS	1.5
Maximum system pressure differential	11.3
Average system pressure value	5.65
Maximum pressure drop along any path	4.9
Minimum pressure at every node	7.9

Temperature-related data (degree Celsius)	
Supply temperature from plant	4.5
Return temperature to plant	12.5
Maximum System temperature differential	8
Maximum temperature rise along any path	0.5
Average system temperature value	1.75
Maximum temperature at every node	6.5

Set of possible pipe sizes with their associated data

Pipe Type	Pipe Inner Diameter (m)	Outer Diameter Including Insulation (m)	Cross Sectional Area (m2)	Unit Cost (QAR/m)	Min. Flow Rate (TR)	Max. Flow Rate (TR)	Vmin (m/s)	Vmax (m/s)
DN200	0.2027	0.28	0	7171.46	0	1563	0	4.6
DN300	0.3033	0.4	0.072249	9139.1	0	3499.906	0	4.6
DN400	0.381	0.5	0.114009	10778.8	0	5522.828	0	4.6
DN500	0.4778	0.56	0.179301	11762.62	0	8685.681	0	4.6
DN600	0.5748	0.71	0	14222.17	0	12570	0	4.6
DN700	0.676173	0.8	0.359092	15697.9	0	17395.13	0	4.6
DN800	0.77785	0.9	0.475205	17337.6	0	23019.87	0	4.6
DN900	0.8763	1	0.603109	18977.3	0	29215.76	0	4.6

DN1000	0.9779	1.1	1	20617	0	36383	0	4.6
DN1200	1.1811	1.3	1.095628	23896.4	0	53074.38	0	4.6
DN1400	1.3843	1.5	1.505048	27175.8	0	72907.47	0	4.6

Cooling demand for each customer

Class 1 - Instance 1

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	600	650	180	900	680	170	1200	400	900	2000
2	800	750	160	1700	880	230	1700	420	1100	2200
3	700	800	300	1650	780	270	1100	500	1000	2900
4	100	300	320	1550	180	220	1700	520	400	2000

Class 1 - Instance 2

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	1200	1300	360	1800	1360	340	2400	800	1800	4000
2	1600	1500	320	3400	1760	460	3400	840	2200	4400
3	1400	1600	600	3300	1560	540	2200	1000	2000	5800
4	200	600	640	3100	360	440	3400	1040	800	4000

Class 1 - Instance 3

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	2400	2600	720	3600	2720	680	4800	1600	3600	8000
2	3200	3000	640	6800	3520	920	6800	1680	4400	8800
3	2800	3200	1200	6600	3120	1080	4400	2000	4000	11600
4	400	1200	1280	6200	720	880	6800	2080	1600	8000

Class 1 - Instance 4

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	4800	5200	1440	7200	5440	1360	9600	3200	7200	16000
2	6400	6000	1280	13600	7040	1840	13600	3360	8800	17600
3	5600	6400	2400	13200	6240	2160	8800	4000	8000	23200
4	800	2400	2560	12400	1440	1760	13600	4160	3200	16000

Class 1 - Instance 5

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	6000	6500	1800	9000	6800	1700	12000	4000	9000	20000
2	8000	7500	1600	17000	8800	2300	17000	4200	11000	22000
3	7000	8000	3000	16500	7800	2700	11000	5000	10000	29000
4	1000	3000	3200	15500	1800	2200	17000	5200	4000	20000

Network Structure									
	Node	**Predecessors**							
Source	0	-	-	-	-	-	-		
Steiner	1	2	6	7	8	-	-		
	2	0	1	7	8	9	-		
	3	8	9	10	-	-	-		
	4	0	10	11	12	13	14		
	5	0	13	14	15	-	-		
Customers	6	1	7	15	-	-	-		
	7	0	1	2	6	15	-		
	8	1	2	3	-	-	-		
	9	0	2	3	10	-	-		
	10	0	3	4	9	11	-		
	11	4	10	12	-	-	-		
	12	4	11	14	-	-	-		
	13	0	4	5	14	-	-		
	14	4	5	12	13	15	-		
	15	0	5	6	7	14	-		
	Node	**Successors**							
Source	0	2	4	5	7	9	10	13	15
Steiner	1	2	6	7	8	-	-	-	-
	2	-	1	7	8	9	-	-	-
	3	8	9	10	-	-	-	-	-
	4	-	10	11	12	13	14	-	-
	5	-	13	14	15	-	-	-	-
Customers	6	1	7	15	-	-	-	-	-
	7	-	1	2	6	15	-	-	-
	8	1	2	3	-	-	-	-	-
	9	-	2	3	10	-	-	-	-
	10	-	3	4	9	11	-	-	-
	11	4	10	12	-	-	-	-	-
	12	4	11	14	-	-	-	-	-
	13	-	4	5	14	-	-	-	-
	14	4	5	12	13	15	-	-	-
	15	-	5	6	7	14	-	-	-

Pipe length between nodes (m)								
Lij	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0	-	-	700	-	750	450	-	850
1	-	-	600	-	-	-	650	350
2	700	600	-	-	-	-	-	250
3	-	-	-	-	-	-	-	-
4	750	-	-	-	-	-	-	-
5	450	-	-	-	-	-	-	-
6	-	650	-	-	-	-	-	550
7	850	350	250	-	-	-	550	-
8	-	400	700	250	-	-	-	-
9	730	-	300	350	-	-	-	-
10	800	-	-	650	700	-	-	-
11	-	-	-	-	400	-	-	-
12	-	-	-	-	375	-	-	-
13	250	-	-	-	500	325	-	-
14	-	-	-	-	800	875	-	-
15	450	-	-	-	-	200	425	600
Lij	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
0	-	730	800	-	-	250	-	450
1	400	-	-	-	-	-	-	-
2	700	300	-	-	-	-	-	-
3	250	350	650	-	-	-	-	-
4	-	-	700	400	375	500	800	-
5	-	-	-	-	-	325	875	200
6	-	-	-	-	-	-	-	425
7	-	-	-	-	-	-	-	600
8	-	-	-	-	-	-	-	-
9	-	-	250	-	-	-	-	-
10	-	250	-	500	-	-	-	-
11	-	-	500	-	425	-	-	-
12	-	-	-	425	-	-	600	-
13	-	-	-	-	-	-	550	-
14	-	-	-	-	600	550	-	950
15	-	-	-	-	-	-	950	-

Data for **Class 2**

Set of possible chiller plant capacities		
k	**Capacity (TR)**	**Fixed Cost (QAR)**
1	5000	54750000
2	8000	87600000
3	10000	120450000
4	18000	183960000
5	25000	189617500
6	30000	224256000
7	40000	292438000
8	60000	438657000
9	75000	548321250
10	80000	584876000
11	100000	731095000

Set of possible storage tank capacities		
h	**Capacity (TR)**	**Fixed Cost (QAR)**
1	2000	6000000
2	4000	12000000
3	8000	24000000
4	12000	36000000
5	16000	48000000
6	20000	60000000
7	25000	75000000
8	30000	90000000
9	40000	120000000

Variable production and storage cost		
Periods (t)	**Variable Cost (QAR)**	
	Production	**Storage**
1	35	10
2	40	10
3	50	10
4	30	10
5	25	10
6	20	10

Pressure-related data (100kPa)	
Supply pressure from plant	12.8
Return pressure to plant	1.5
Minimum pressure differential at ETS	1.5
Maximum system pressure differential	11.3
Average system pressure value	5.65
Maximum pressure drop along any path	4.9
Minimum pressure at every node	7.9

Temperature-related data (degree Celsius)	
Supply temperature from plant	4.5
Return temperature to plant	12.5
Maximum System temperature differential	8
Maximum temperature rise along any path	0.5
Average system temperature value	1.75
Maximum temperature at every node	6.5

Set of possible pipe sizes with their associated data								
Pipe Type	**Pipe Inner Diameter (m)**	**Outer Diameter Including Insulation (m)**	**Cross Sectional Area (m2)**	**Unit Cost (QAR/m)**	**Min. Flow Rate (TR)**	**Max. Flow Rate (TR)**	**Vmin (m/s)**	**Vmax (m/s)**
DN200	0.2027	0.28	0	7171.46	0	1563	0	4.6
DN300	0.3033	0.4	0.072249	9139.1	0	3499.906	0	4.6
DN400	0.381	0.5	0.114009	10778.8	0	5522.828	0	4.6
DN500	0.4778	0.56	0.179301	11762.62	0	8685.681	0	4.6
DN600	0.5748	0.71	0	14222.17	0	12570	0	4.6
DN700	0.676173	0.8	0.359092	15697.9	0	17395.13	0	4.6
DN800	0.77785	0.9	0.475205	17337.6	0	23019.87	0	4.6
DN900	0.8763	1	0.603109	18977.3	0	29215.76	0	4.6

DN1000	0.9779	1.1	1	20617	0	36383	0	4.6
DN1200	1.1811	1.3	1.095628	23896.4	0	53074.38	0	4.6
DN1400	1.3843	1.5	1.505048	27175.8	0	72907.47	0	4.6

Cooling demand for each customer

Class 2 - Instance 1

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	50	470	95	280	300	550	700	450	1400	660
2	80	500	120	330	500	700	900	550	1600	700
3	60	510	120	400	450	720	910	600	1400	800
4	55	400	100	380	430	700	940	610	1500	900
5	70	350	95	290	400	680	800	550	1000	1000
6	50	400	95	280	500	650	750	400	1000	1100
Periods	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
1	1450	75	100	800	1200	420	60	80	180	300
2	1000	60	200	950	1000	300	90	80	190	150
3	1000	70	200	900	1000	300	100	85	200	175
4	1200	50	100	700	1100	320	80	80	150	175
5	1000	60	200	620	1000	200	100	100	190	300
6	950	65	200	800	1200	100	90	100	160	400

Class 2 - Instance 2

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	100	940	190	560	600	500	1400	900	2800	1320
2	160	1000	240	660	1000	1400	1800	1100	1600	1400
3	120	1020	240	800	900	1440	1820	1200	2800	1600
4	110	800	200	760	860	1400	1880	1220	3000	1800
5	140	700	190	580	800	1360	1600	1100	2000	2000
6	100	800	190	560	1000	1300	1500	800	2000	1100
Periods	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
1	2900	150	200	1600	2400	840	120	160	360	600
2	2000	120	400	1900	2000	600	180	160	380	300
3	2000	140	400	1800	2000	600	200	170	400	350
4	2400	100	200	1400	2200	640	160	160	300	350
5	2000	120	400	1240	2000	400	200	200	190	300
6	1900	130	400	1600	2400	200	180	200	160	400

Class 2 - Instance 3

Periods	Customers									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	200	1880	380	1120	1200	2200	2800	1800	5600	2640

2	320	2000	480	1320	2000	2800	3600	2200	6400	2800
3	240	2040	480	1600	1800	2880	3640	2400	5600	3200
4	220	1600	400	1520	1720	2800	3760	2440	6000	3600
5	280	1400	380	1160	1600	2720	3200	2200	1000	4000
6	200	1600	380	1120	2000	2600	3000	1600	1000	1100
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	5800	300	400	3200	4800	1680	240	320	720	1200
2	4000	240	800	3800	1000	1200	360	320	760	600
3	4000	280	800	3600	4000	1200	400	340	800	700
4	4800	200	400	2800	4400	1280	320	320	600	700
5	4000	240	800	2480	4000	800	400	400	760	1200
6	3800	260	800	3200	4800	400	360	400	640	1600

Class 2 - Instance 4

Periods	**Customers**									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
1	400	3760	760	2240	2400	4400	5600	3600	11200	660
2	640	4000	960	2640	4000	5600	7200	4400	12800	5600
3	480	4080	960	3200	3600	5760	7280	4800	11200	6400
4	440	3200	800	3040	3440	5600	7520	4880	12000	7200
5	560	2800	760	2320	3200	5440	6400	4400	8000	8000
6	400	3200	760	2240	4000	5200	6000	3200	8000	8800
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	11600	600	800	6400	9600	3360	480	640	1440	2400
2	8000	480	1600	7600	8000	2400	720	640	1520	1200
3	8000	560	1600	7200	8000	2400	800	680	1600	1400
4	9600	400	800	5600	8800	2560	640	640	1200	1400
5	8000	480	1600	4960	1000	1600	800	800	1520	2400
6	7600	520	200	6400	9600	800	720	800	1280	3200

Class 2 - Instance 5

Periods	**Customers**									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
1	100	4700	950	2800	3000	5500	7000	4500	14000	6600
2	100	5000	1200	3300	5000	7000	9000	5500	16000	7000
3	600	5100	1200	4000	4500	7200	9100	6000	14000	8000
4	120	4000	1000	3800	4300	7000	9400	6100	15000	9000
5	130	3500	950	2900	4000	6800	8000	5500	10000	10000
6	100	4000	950	2800	5000	6500	7500	4000	10000	11000
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	14500	750	1000	8000	12000	4200	600	200	1800	3000
2	10000	600	2000	9500	10000	3000	900	100	1900	1500
3	10000	700	2000	9000	10000	3000	1000	850	2000	1750

4	12000	500	1000	7000	11000	3200	800	200	1500	1750
5	10000	600	2000	6200	10000	2000	1000	200	1900	3000
6	9500	650	2000	8000	12000	1000	900	100	1600	4000

Network Structure

	Node	**Predecessors**						
Source	0	-	-	-	-	-	-	-
Steiner	1	11	10	27	28	-	-	-
	2	0	3	14	15	29	-	-
	3	2	13	14	15	16	17	-
	4	0	15	17	18	19	-	-
	5	0	18	19	20	25	-	-
	6	19	20	21	-	-	-	-
	7	20	22	24	25	-	-	-
	8	9	22	24	25	26	-	-
	9	8	24	26	27	-	-	-
	10	0	25	28	29	30	-	-
Customer	11	1	12	13	-	-	-	-
	12	1	11	13	14	-	-	-
	13	3	11	12	14	16	-	-
	14	2	3	12	13	-	-	-
	15	0	2	3	4	17	18	-
	16	3	13	17	18	-	-	-
	17	3	4	15	16	18	-	-
	18	4	5	15	17	19	-	-
	19	4	5	6	18	-	-	-
	20	5	6	7	21	25	-	-
	21	6	20	22	23	-	-	-
	22	7	8	21	23	-	-	-
	23	21	22	24	-	-	-	-
	24	7	8	9	23	27	-	-
	25	0	5	7	8	10	20	26
	26	8	9	25	27	28	-	-
	27	9	24	26	28	30	-	-
	28	0	10	26	27	30	-	-
	29	0	1	2	10	30	-	-
	30	1	10	27	28	29	-	-

	Node	**Successors**							
Source	0	2	4	5	10	15	25	28	29
Steiner	1	11	10	27	28	-	-	-	-
	2	-	3	14	15	29	-	-	-
	3	2	13	14	15	16	17	-	-
	4	-	15	17	18	19	-	-	-

	5	-	18	19	20	25	-	-	-
	6	19	20	21	-	-	-	-	-
	7	20	22	24	25	-	-	-	-
	8	9	22	24	25	26	-	-	-
	9	8	24	26	27	-	-	-	-
	10	-	25	28	29	30	-	-	-
Customer	11	1	12	13	-	-	-	-	-
	12	1	11	13	14	-	-	-	-
	13	3	11	12	14	16	-	-	-
	14	2	3	12	13	-	-	-	-
	15	-	2	3	4	17	18	-	-
	16	3	13	17	18	-	-	-	-
	17	3	4	15	16	18	-	-	-
	18	4	5	15	17	19	-	-	-
	19	4	5	6	18	-	-	-	-
	20	5	6	7	21	25	-	-	-
	21	6	20	22	23	-	-	-	-
	22	7	8	21	23	-	-	-	-
	23	21	22	24	-	-	-	-	-
	24	7	8	9	23	27	-	-	-
	25	-	5	7	8	10	20	26	-
	26	8	9	25	27	28	-	-	-
	27	9	24	26	28	30	-	-	-
	28	-	10	26	27	30	-	-	-
	29	-	1	2	10	30	-	-	-
	30	1	10	27	28	29	-	-	-

Pipe length between nodes (m)								
Lij	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0	-	-	600	-	375	325	-	-
2	-	-	-	-	-	-	-	-
3	600	-	-	325	-	-	-	-
3	-	-	325	-	-	-	-	-
4	375	-	-	-	-	-	-	-
5	325	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	300	-	-	-	-	-	-	-
11	-	175	-	-	-	-	-	-

12	-	200	-	-	-	-	-	-
13	-	-	-	450	-	-	-	-
14	-	-	100	350	-	-	-	-
15	500	-	150	400	300	-	-	-
16	-	-	-	375	-	-	-	-
17	-	-	-	325	400	-	-	-
18	-	-	-	-	250	500	-	-
19	-	-	-	-	300	350	250	-
20	-	-	-	-	-	200	300	175
21	-	-	-	-	-	-	275	-
22	-	-	-	-	-	-	-	300
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	750
25	300	-	-	-	-	350	-	400
26	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-
28	400	-	-	-	-	-	-	-
29	250	225	400	-	-	-	-	-
30	-	250	-	-	-	-	-	-

Lij	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
0	-	-	300	-	-	-	-	500
2	-	-	-	175	200	-	-	-
3	-	-	-	-	-	-	100	150
3	-	-	-	-	-	450	350	400
4	-	-	-	-	-	-	-	300
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	375	-	-	-	-	-	-
9	375	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-
11	-	-	-	-	450	400	-	-
12	-	-	-	450	-	375	325	-
13	-	-	-	400	375	-	300	-
14	-	-	-	-	325	300	-	-
15	-	-	-	-	-	-	-	-
16	-	-	-	-	-	750	-	-
17	-	-	-	-	-	-	-	400
18	-	-	-	-	-	-	-	425
19	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	650	-	-	-	-	-	-	-

23	-	-	-	-	-	-	-	-
24	550	300	-	-	-	-	-	-
25	200	-	375	-	-	-	-	-
26	325	400	-	-	-	-	-	-
27	-	450	-	-	-	-	-	-
28	-	-	175	-	-	-	-	-
29	-	-	150	-	-	-	-	-
30	-	-	375	-	-	-	-	-
Lij	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
0	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
3	375	325	-	-	-	-	-	-
4	-	400	250	300	-	-	-	-
5	-	-	500	350	200	-	-	-
6	-	-	-	250	300	275	-	-
7	-	-	-	-	175	-	300	-
8	-	-	-	-	-	-	650	-
9	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-
13	750	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-
15	-	400	425	-	-	-	-	-
16	-	300	600	-	-	-	-	-
17	300	-	325	-	-	-	-	-
18	600	325	-	550	-	-	-	-
19	-	-	550	-	-	-	-	-
20	-	-	-	-	-	375	-	-
21	-	-	-	-	375	-	175	350
22	-	-	-	-	-	175	-	150
23	-	-	-	-	-	350	150	-
24	-	-	-	-	-	-	-	700
25	-	-	-	-	400	-	-	-
26	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-	-
29	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-
Lij	**24**	**25**	**26**	**27**	**28**	**29**		
0	-	300	-	-	400	250		
2	-	-	-	-	-	225		

3	-	-	-	-	-	400		
3	-	-	-	-	-	-		
4	-	-	-	-	-	-		
5	-	350	-	-	-	-		
6	-	-	-	-	-	-		
7	750	400	-	-	-	-		
8	550	200	325	-	-	-		
9	300	-	400	450	-	-		
10	-	375	-	-	175	150		
11	-	-	-	-	-	-		
12	-	-	-	-	-	-		
13	-	-	-	-	-	-		
14	-	-	-	-	-	-		
15	-	-	-	-	-	-		
16	-	-	-	-	-	-		
17	-	-	-	-	-	-		
18	-	-	-	-	-	-		
19	-	-	-	-	-	-		
20	-	400	-	-	-	-		
21	-	-	-	-	-	-		
22	-	-	-	-	-	-		
23	700	-	-	-	-	-		
24	-	-	-	600	-	-		
25	-	-	400	-	-	-		
26	-	400	-	425	500	-		
27	600	-	425	-	750	-		
28	-	-	500	750	-	-		
29	-	-	-	-	-	-		
30	-	-	-	900	525	300		

Data for **Class 3**

Set of possible chiller plant capacities		
k	**Capacity (TR)**	**Fixed Cost (QAR)**
1	5000	54750000
2	8000	87600000
3	10000	120450000
4	18000	183960000
5	25000	189617500
6	30000	224256000
7	40000	292438000
8	60000	438657000
9	75000	548321250
10	80000	584876000
11	100000	731095000

Set of possible storage tank capacities		
h	**Capacity (TR)**	**Fixed Cost (QAR)**
1	2000	6000000
2	4000	12000000
3	8000	24000000
4	12000	36000000
5	16000	48000000
6	20000	60000000
7	25000	75000000
8	30000	90000000
9	40000	120000000

Variable production and storage cost		
Periods (t)	**Variable Cost (QAR)**	
	Production	**Storage**
1	35	20
2	40	20
3	50	20
4	50	20
5	50	20
6	40	20
7	30	20
8	30	20

Pressure-related data (100kPa)	
Supply pressure from plant	12.8
Return pressure to plant	1.5
Minimum pressure differential at ETS	1.5
Maximum system pressure differential	11.3
Average system pressure value	5.65
Maximum pressure drop along any path	4.9
Minimum pressure at every node	7.9

Temperature-related data (degree Celsius)	
Supply temperature from plant	4.5
Return temperature to plant	12.5
Maximum System temperature differential	8
Maximum temperature rise along any path	0.5
Average system temperature value	1.75
Maximum temperature at every node	6.5

Set of possible pipe sizes with their associated data								
Pipe Type	**Pipe Inner Diameter (m)**	**Outer Diameter Including Insulation (m)**	**Cross Sectional Area (m2)**	**Unit Cost (QAR/m)**	**Min. Flow Rate (TR)**	**Max. Flow Rate (TR)**	**Vmin (m/s)**	**Vmax (m/s)**
DN200	0.2027	0.28	0	7171.46	0	1563	0	4.6
DN300	0.3033	0.4	0.072249	9139.1	0	3499.906	0	4.6
DN400	0.381	0.5	0.114009	10778.8	0	5522.828	0	4.6
DN500	0.4778	0.56	0.179301	11762.62	0	8685.681	0	4.6
DN600	0.5748	0.71	0	14222.17	0	12570	0	4.6
DN700	0.676173	0.8	0.359092	15697.9	0	17395.13	0	4.6
DN800	0.77785	0.9	0.475205	17337.6	0	23019.87	0	4.6
DN900	0.8763	1	0.603109	18977.3	0	29215.76	0	4.6

DN1000	0.9779	1.1	1	20617	0	36383	0	4.6
DN1200	1.1811	1.3	1.095628	23896.4	0	53074.38	0	4.6
DN1400	1.3843	1.5	1.505048	27175.8	0	72907.47	0	4.6

Cooling demand for each customer										
Class 3 - Instance 1										
Periods	**Customers**									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
1	100	120	0	200	50	90	130	140	90	200
2	120	130	0	350	60	100	150	200	100	200
3	300	500	300	500	120	300	130	230	130	250
4	400	450	400	300	130	300	150	280	150	250
5	350	500	350	100	200	150	170	300	200	200
6	300	350	400	0	400	100	190	200	130	200
7	120	200	0	0	200	90	210	290	100	200
8	100	180	0	0	100	90	230	140	90	200
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	300	240	300	90	120	140	120	140	20	220
2	400	250	350	120	140	160	140	150	20	370
3	300	400	350	150	140	200	320	300	200	220
4	280	500	300	130	150	220	400	350	200	250
5	270	150	100	120	150	280	370	520	370	120
6	250	100	0	90	150	300	320	370	420	200
7	150	0	0	80	130	200	140	220	20	200
8	100	0	0	80	120	100	120	200	20	200
Periods	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**	**C27**	**C28**	**C29**	**C30**
1	70	110	150	160	110	400	320	260	320	110
2	80	120	170	220	120	400	420	270	370	140
3	140	250	150	230	150	350	280	270	370	170
4	150	200	170	230	170	200	300	200	320	150
5	220	170	190	320	220	220	290	170	120	140
6	420	120	210	220	150	220	270	120	20	110
7	220	110	230	310	120	220	170	20	20	100
8	120	110	250	160	110	220	120	20	20	100
Periods	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**	**C38**	**C39**	**C40**
1	140	160	140	160	40	240	90	130	170	180
2	160	180	160	170	40	390	100	140	190	240
3	160	220	340	320	220	240	160	270	170	200
4	170	240	350	280	220	270	170	220	190	200
5	170	300	390	285	390	140	240	190	210	340
6	170	320	340	390	440	220	440	140	230	240

7	150	220	160	240	40	220	240	130	250	330
8	140	120	140	220	40	220	140	130	270	180

Class 3 - Instance 2

Periods	Customers									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
1	100	120	160	200	240	140	150	110	260	400
2	120	130	170	260	220	170	120	100	240	360
3	160	140	120	300	200	160	100	100	280	400
4	180	150	130	280	260	140	110	110	300	360
5	200	180	130	240	240	150	100	120	360	360
6	150	180	140	200	220	140	160	140	320	440
7	150	120	160	180	200	130	160	160	310	450
8	120	100	160	190	100	120	150	100	240	200
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	180	240	170	260	450	200	800	620	1200	1440
2	180	620	160	220	400	820	1140	600	1220	1400
3	160	560	180	240	460	900	1160	680	1300	1380
4	150	600	160	220	300	600	1240	900	1400	1440
5	160	550	200	200	440	820	1300	820	1200	1300
6	200	500	260	240	400	900	1200	920	1240	1220
7	220	460	200	180	380	820	1100	820	1300	800
8	260	420	250	170	440	240	1200	800	1200	1260
Periods	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**	**C27**	**C28**	**C29**	**C30**
1	440	160	700	700	660	240	1300	120	180	170
2	460	200	740	1600	800	320	1400	140	200	180
3	460	190	780	1800	820	340	1440	160	240	200
4	500	220	820	2000	640	370	1440	180	260	170
5	600	200	600	1900	700	320	1600	180	200	180
6	580	170	800	1600	640	300	240	200	190	190
7	420	200	770	1400	700	330	420	180	180	200
8	500	220	800	1200	600	320	320	150	180	160
Periods	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**	**C38**	**C39**	**C40**
1	220	200	420	100	150	200	260	400	180	1100
2	240	700	450	120	160	260	300	480	1000	1200
3	220	680	400	130	180	240	360	440	1100	840
4	200	640	380	140	190	260	280	400	900	600
5	220	600	440	160	200	280	300	420	800	500
6	170	620	500	180	240	320	320	200	640	660
7	160	580	530	200	160	340	240	180	600	400
8	190	200	420	100	180	200	200	240	240	600

Class 3 - Instance 3

Periods	Customers

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	200	240	320	400	480	280	300	220	520	800
2	240	260	340	520	440	340	240	200	480	720
3	320	280	240	600	400	320	200	200	560	800
4	360	300	260	560	520	280	220	220	600	720
5	400	360	260	480	480	300	200	240	720	720
6	300	360	280	400	440	280	320	280	640	880
7	300	240	320	360	400	260	320	320	620	900
8	240	200	320	380	200	240	300	200	480	400
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	360	480	340	520	900	400	1600	1240	2400	2880
2	360	1240	320	440	800	1640	2280	1200	2440	2800
3	320	1120	360	480	920	1800	2320	1360	2600	2760
4	300	1200	320	440	600	1200	2480	1800	2800	2880
5	320	1100	400	400	880	1640	2600	1640	2400	2600
6	400	1000	520	480	800	1800	2400	1840	2480	2440
7	440	920	400	360	760	1640	2200	1640	2600	1600
8	520	840	500	340	880	480	2400	1600	2400	2520
Periods	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**	**C27**	**C28**	**C29**	**C30**
1	880	320	1400	1400	1320	480	2600	240	360	340
2	920	400	1480	3200	1600	640	2800	280	400	360
3	920	380	1560	3600	1640	680	2880	320	480	400
4	1000	440	1640	4000	1280	740	2880	360	520	340
5	1200	400	1200	3800	1400	640	3200	360	400	360
6	1160	340	1600	3200	1280	600	480	400	380	380
7	840	400	1540	2800	1400	660	840	360	360	400
8	1000	440	1600	2400	1200	640	640	300	360	320
Periods	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**	**C38**	**C39**	**C40**
1	440	400	840	200	300	400	520	800	360	2200
2	480	1400	900	240	320	520	600	960	2000	2400
3	440	1360	800	260	360	480	720	880	2200	1680
4	400	1280	760	280	380	520	560	800	1800	1200
5	440	1200	880	320	400	560	600	840	1600	1000
6	340	1240	1000	360	480	640	640	400	1280	1320
7	320	1160	1060	400	320	680	480	360	1200	800
8	380	400	840	200	360	400	400	480	480	1200

Class 3 - Instance 4

Periods	Customers									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
1	400	480	640	800	960	560	600	440	1040	1600
2	480	520	680	1040	880	680	480	400	960	1440
3	640	560	480	1200	800	640	400	400	1120	1600

4	720	600	520	1120	1040	560	440	440	1200	1440
5	800	720	520	960	960	600	400	480	1440	1440
6	600	720	560	800	880	560	640	560	1280	1760
7	600	480	640	720	800	520	640	640	1240	1800
8	480	400	640	760	400	480	600	400	960	800
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	720	960	680	1040	1800	800	3200	2480	4800	5760
2	720	2480	640	880	1600	3280	4560	2400	4880	5600
3	640	2240	720	960	1840	3600	4640	2720	5200	5520
4	600	2400	640	880	1200	2400	4960	3600	5600	5760
5	640	2200	800	800	1760	3280	5200	3280	4800	5200
6	800	2000	1040	960	1600	3600	4800	3680	4960	4880
7	880	1840	800	720	1520	3280	4400	3280	5200	3200
8	1040	1680	1000	680	1760	960	4800	3200	4800	5040
Periods	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**	**C27**	**C28**	**C29**	**C30**
1	1760	640	2800	2800	2640	960	5200	480	720	680
2	1840	800	2960	6400	3200	1280	5600	560	800	720
3	1840	760	3120	7200	3280	1360	5760	640	960	800
4	2000	880	3280	8000	2560	1480	5760	720	1040	680
5	2400	800	2400	7600	2800	1280	6400	720	800	720
6	2320	680	3200	6400	2560	1200	960	800	760	760
7	1680	800	3080	5600	2800	1320	1680	720	720	800
8	2000	880	3200	4800	2400	1280	1280	600	720	640
Periods	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**	**C38**	**C39**	**C40**
1	880	800	1680	400	600	800	1040	1600	720	4400
2	960	2800	1800	480	640	1040	1200	1920	4000	4800
3	880	2720	1600	520	720	960	1440	1760	4400	3360
4	800	2560	1520	560	760	1040	1120	1600	3600	2400
5	880	2400	1760	640	800	1120	1200	1680	3200	2000
6	680	2480	2000	720	960	1280	1280	800	2560	2640
7	640	2320	2120	800	640	1360	960	720	2400	1600
8	760	800	1680	400	720	800	800	960	960	2400

Class 3 - Instance 5										
Periods	**Customers**									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
1	500	600	800	1000	1200	700	750	550	1300	2000
2	600	650	850	1300	1100	850	600	500	1200	1800
3	800	700	600	1500	1000	800	500	500	1400	2000
4	900	750	650	1400	1300	700	550	550	1500	1800
5	1000	900	650	1200	1200	750	500	600	1800	1800
6	750	900	700	1000	1100	700	800	700	1600	2200
7	750	600	800	900	1000	650	800	800	1550	2250

8	600	500	800	950	500	600	750	500	1200	1000
Periods	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
1	900	1200	850	1300	2250	1000	4000	3100	6000	7200
2	900	3100	800	1100	2000	4100	5700	3000	6100	7000
3	800	2800	900	1200	2300	4500	5800	3400	6500	6900
4	750	3000	800	1100	1500	3000	6200	4500	7000	7200
5	800	2750	1000	1000	2200	4100	6500	4100	6000	6500
6	1000	2500	1300	1200	2000	4500	6000	4600	6200	6100
7	1100	2300	1000	900	1900	4100	5500	4100	6500	4000
8	1300	2100	1250	850	2200	1200	6000	4000	6000	6300
Periods	**C21**	**C22**	**C23**	**C24**	**C25**	**C26**	**C27**	**C28**	**C29**	**C30**
1	2200	800	3500	3500	3300	1200	6500	600	900	850
2	2300	1000	3700	8000	4000	1600	7000	700	1000	900
3	2300	950	3900	9000	4100	1700	7200	800	1200	1000
4	2500	1100	4100	10000	3200	1850	7200	900	1300	850
5	3000	1000	3000	9500	3500	1600	8000	900	1000	900
6	2900	850	4000	8000	3200	1500	1200	1000	950	950
7	2100	1000	3850	7000	3500	1650	2100	900	900	1000
8	2500	1100	4000	6000	3000	1600	1600	750	900	800
Periods	**C31**	**C32**	**C33**	**C34**	**C35**	**C36**	**C37**	**C38**	**C39**	**C40**
1	1100	1000	2100	500	750	1000	1300	2000	900	5500
2	1200	3500	2250	600	800	1300	1500	2400	5000	6000
3	1100	3400	2000	650	900	1200	1800	2200	5500	4200
4	1000	3200	1900	700	950	1300	1400	2000	4500	3000
5	1100	3000	2200	800	1000	1400	1500	2100	4000	2500
6	850	3100	2500	900	1200	1600	1600	1000	3200	3300
7	800	2900	2650	1000	800	1700	1200	900	3000	2000
8	950	1000	2100	500	900	1000	1000	1200	1200	3000

Network Structure									
	Node	**Predecessors**							
Source	0	-	-	-	-	-	-	-	-
Steiner	1	21	22	23	24	-	-	-	-
	2	25	27	58	-	-	-	-	-
	3	24	26	29	-	-	-	-	-
	4	26	28	29	30	31	-	-	-
	5	27	28	31	32	56	-	-	-
	6	0	32	33	36	-	-	-	-
	7	29	30	33	34	-	-	-	-
	8	33	34	35	-	-	-	-	-

	9	35	37	39	40	-	-	-	-
	10	38	40	42	-	-	-	-	-
	11	40	41	42	-	-	-	-	-
	12	41	42	43	-	-	-	-	-
	13	43	44	45	-	-	-	-	-
	14	42	46	47	48	-	-	-	-
	15	16	48	53	54	-	-	-	-
	16	15	49	51	52	53	-	-	-
	17	53	54	55	-	-	-	-	-
	18	0	19	46	47	56	-	-	-
	19	18	47	54	55	56	57	-	-
	20	57	58	59	-	-	-	-	-
	21	1	22	-	-	-	-	-	-
	22	1	21	23	59	60	-	-	-
	23	1	22	24	26	58	-	-	-
	24	1	3	23	25	-	-	-	-
	25	2	24	26	27	59	-	-	-
	26	3	4	23	25	-	-	-	-
	27	2	5	25	28	56	-	-	-
	28	4	5	27	29	-	-	-	-
	29	3	4	7	28	30	-	-	-
	30	4	7	29	33	-	-	-	-
	31	4	5	32	33	-	-	-	-
	32	0	5	6	31	56	-	-	-
	33	6	7	8	30	31	35	-	-
Customer	34	7	8	-	-	-	-	-	-
	35	8	9	33	36	-	-	-	-
	36	6	35	37	-	-	-	-	-
	37	9	36	38	-	-	-	-	-
	38	0	10	37	46	-	-	-	-
	39	9	40	41	-	-	-	-	-
	40	9	10	11	39	-	-	-	-
	41	11	12	39	43	44	-	-	-
	42	10	11	12	14	46	50	-	-
	43	12	13	41	45	50	-	-	-
	44	13	41	50	-	-	-	-	-
	45	13	43	50	-	-	-	-	-
	46	14	18	38	42	-	-	-	-
	47	14	18	19	48	54	-	-	-
	48	14	15	47	49	54	-	-	-

	49	12	16	48	50	51	-	-	-
	50	42	43	44	45	49	51	-	-
	51	16	49	50	52	-	-	-	-
	52	16	51	53	-	-	-	-	-
	53	15	16	17	52	54	-	-	-
	54	15	17	19	47	48	53	-	-
	55	17	19	57	-	-	-	-	-
	56	0	5	18	19	27	32	57	58
	57	19	20	55	56	58	60	-	-
	58	2	20	23	56	57	-	-	-
	59	20	22	25	60	-	-	-	-
	60	22	57	59	-	-	-	-	-

	Node	**Successors**							
Source	0	6	18	32	38	56	-	-	-
Steiner	1	21	22	23	24	-	-	-	-
	2	25	27	58	-	-	-	-	-
	3	24	26	29	-	-	-	-	-
	4	26	28	29	30	31	-	-	-
	5	27	28	31	32	56	-	-	-
	6	-	32	33	36	-	-	-	-
	7	29	30	33	34	-	-	-	-
	8	33	34	35	-	-	-	-	-
	9	35	37	39	40	-	-	-	-
	10	38	40	42	-	-	-	-	-
	11	40	41	42	-	-	-	-	-
	12	41	42	43	-	-	-	-	-
	13	43	44	45	-	-	-	-	-
	14	42	46	47	48	-	-	-	-
	15	16	48	53	54	-	-	-	-
	16	15	49	51	52	53	-	-	-
	17	53	54	55	-	-	-	-	-
	18	-	19	46	47	56	-	-	-
	19	18	47	54	55	56	57	-	-
	20	57	58	59	-	-	-	-	-
Customer	21	1	22	-	-	-	-	-	-
	22	1	21	23	59	60	-	-	-
	23	1	22	24	26	58	-	-	-
	24	1	3	23	25	-	-	-	-
	25	2	24	26	27	59	-	-	-
	26	3	4	23	25	-	-	-	-
	27	2	5	25	28	56	-	-	-

	28	4	5	27	29	-	-	-	-
	29	3	4	7	28	30	-	-	-
	30	4	7	29	33	-	-	-	-
	31	4	5	32	33	-	-	-	-
	32	-	5	6	31	56	-	-	-
	33	6	7	8	30	31	35	-	-
	34	7	8	-	-	-	-	-	-
	35	8	9	33	36	-	-	-	-
	36	6	35	37	-	-	-	-	-
	37	9	36	38	-	-	-	-	-
	38	-	10	37	46	-	-	-	-
	39	9	40	41	-	-	-	-	-
	40	9	10	11	39	-	-	-	-
	41	11	12	39	43	44	-	-	-
	42	10	11	12	14	46	50	-	-
	43	12	13	41	45	50	-	-	-
	44	13	41	50	-	-	-	-	-
	45	13	43	50	-	-	-	-	-
	46	14	18	38	42	-	-	-	-
	47	14	18	19	48	54	-	-	-
	48	14	15	47	49	54	-	-	-
	49	12	16	48	50	51	-	-	-
	50	42	43	44	45	49	51	-	-
	51	16	49	50	52	-	-	-	-
	52	16	51	53	-	-	-	-	-
	53	15	16	17	52	54	-	-	-
	54	15	17	19	47	48	53	-	-
	55	17	19	57	-	-	-	-	-
	56	-	5	18	19	27	32	57	58
	57	19	20	55	56	58	60	-	-
	58	2	20	23	56	57	-	-	-
	59	20	22	25	60	-	-	-	-
	60	22	57	59	-	-	-	-	-

Pipe length between nodes (m)

Lij	0	1	2	3	4	5	6	7
0	-	-	-	-	-	-	300	-
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-

6	300	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-
18	185	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-
21	-	100	-	-	-	-	-	-
22	-	225	-	-	-	-	-	-
23	-	180	-	-	-	-	-	-
24	-	200	-	330	-	-	-	-
25	-	-	200	-	-	-	-	-
26	-	-	-	285	350	-	-	-
27	-	-	200	-	-	200	-	-
28	-	-	-	-	210	310	-	-
29	-	-	-	200	220	-	-	420
30	-	-	-	-	225	-	-	260
31	-	-	-	-	280	180	-	-
32	100	-	-	-	-	130	400	-
33	-	-	-	-	-	-	250	390
34	-	-	-	-	-	-	-	200
35	-	-	-	-	-	-	-	-
36	-	-	-	-	-	-	230	-
37	-	-	-	-	-	-	-	-
38	150	-	-	-	-	-	-	-
39	-	-	-	-	-	-	-	-
40	-	-	-	-	-	-	-	-
41	-	-	-	-	-	-	-	-
42	-	-	-	-	-	-	-	-
43	-	-	-	-	-	-	-	-
44	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-
46	-	-	-	-	-	-	-	-
47	-	-	-	-	-	-	-	-
48	-	-	-	-	-	-	-	-

49	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-
51	-	-	-	-	-	-	-	-
52	-	-	-	-	-	-	-	-
53	-	-	-	-	-	-	-	-
54	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-
56	225	-	-	-	-	300	-	-
57	-	-	-	-	-	-	-	-
58	-	-	320	-	-	-	-	-
59	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-
Lij	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
0	-	-	-	-	-	-	-	-
1	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	320
17	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-	-
29	-	-	-	-	-	-	-	-

30	-	-	-	-	-	-	-	-
31	-	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-	-
33	150	-	-	-	-	-	-	-
34	160	-	-	-	-	-	-	-
35	170	310	-	-	-	-	-	-
36	-	-	-	-	-	-	-	-
37	-	160	-	-	-	-	-	-
38	-	-	100	-	-	-	-	-
39	-	100	-	-	-	-	-	-
40	-	270	170	110	-	-	-	-
41	-	-	-	120	130	-	-	-
42	-	-	300	130	160	-	240	-
43	-	-	-	-	140	200	-	-
44	-	-	-	-	-	210	-	-
45	-	-	-	-	-	185	-	-
46	-	-	-	-	-	-	225	-
47	-	-	-	-	-	-	300	-
48	-	-	-	-	-	-	170	280
49	-	-	-	-	550	-	-	-
50	-	-	-	-	-	-	-	-
51	-	-	-	-	-	-	-	-
52	-	-	-	-	-	-	-	-
53	-	-	-	-	-	-	-	290
54	-	-	-	-	-	-	-	330
55	-	-	-	-	-	-	-	-
56	-	-	-	-	-	-	-	-
57	-	-	-	-	-	-	-	-
58	-	-	-	-	-	-	-	-
59	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-
Lij	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
0	-	-	185	-	-	-	-	-
1	-	-	-	-	-	100	225	180
2	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-

11	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-
15	320	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-
18	-	-	-	330	-	-	-	-
19	-	-	330	-	-	-	-	-
20	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	175	-
22	-	-	-	-	-	175	-	200
23	-	-	-	-	-	-	200	-
24	-	-	-	-	-	-	-	140
25	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	290
27	-	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-	-
29	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-
31	-	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-	-
33	-	-	-	-	-	-	-	-
34	-	-	-	-	-	-	-	-
35	-	-	-	-	-	-	-	-
36	-	-	-	-	-	-	-	-
37	-	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-	-
39	-	-	-	-	-	-	-	-
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48	-	-	-	-	-	-	-	-
49	320	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-
51	290	-	-	-	-	-	-	-
52	200	-	-	-	-	-	-	-
53	250	340	-	-	-	-	-	-

54	-	120	-	300	-	-	-	-
55	-	270	-	285	-	-	-	-
56	-	-	280	275	-	-	-	-
57	-	-	-	310	210	-	-	-
58	-	-	-	-	230	-	-	600
59	-	-	-	-	250	-	310	-
60	-	-	-	-	-	-	330	-
Lij	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
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2	-	200	-	200	-	-	-	-
3	330	-	285	-	-	200	-	-
4	-	-	350	-	210	220	225	280
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6	-	-	-	-	-	-	-	-
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23	140	-	290	-	-	-	-	-
24	-	400	-	-	-	-	-	-
25	400	-	220	310	-	-	-	-
26	-	220	-	-	-	-	-	-
27	-	310	-	-	190	-	-	-
28	-	-	-	190	-	235	-	-
29	-	-	-	-	235	-	220	-
30	-	-	-	-	-	220	-	-
31	-	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-	240
33	-	-	-	-	-	-	310	285
34	-	-	-	-	-	-	-	-

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37	-	-	-	-	-	-	-	-
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3	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-
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6	400	250	-	-	230	-	-	-
7	-	390	200	-	-	-	-	-
8	-	150	160	170	-	-	-	-
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31	240	285	-	-	-	-	-	-
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36	-	-	-	270	-	185	-	-
37	-	-	-	-	185	-	310	-
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41	-	-	-	-	-	-	-	525
42	-	-	-	-	-	-	-	-
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44	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-
46	-	-	-	-	-	-	275	-
47	-	-	-	-	-	-	-	-
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55	-	-	-	-	-	-	-	-
56	310	-	-	-	-	-	-	-
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59	-	-	-	-	-	-	-	-
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9	270	-	-	-	-	-	-	-
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11	110	120	130	-	-	-	-	-
12	-	130	160	140	-	-	-	-
13	-	-	-	200	210	185	-	-
14	-	-	240	-	-	-	225	300
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39	310	525	-	-	-	-	-	-

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43	-	400	-	-	-	240	-	-
44	-	600	-	-	-	-	-	-
45	-	-	-	240	-	-	-	-
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47	-	-	-	-	-	-	-	-
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53	-	-	-	-	-	-	-	-
54	-	-	-	-	-	-	-	210
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14	170	-	-	-	-	-	-	-
15	280	-	-	-	-	290	330	-
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23	-	-	600	-				
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58	220	300	-	-				
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