THE PATH TO DEVELOPMENT OF AN INTEGRATED TOOL FOR DISTRICT COOLING SYSTEMS MODELLING, SIMULATION, AND CONTROL

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ABSTRACT

The reviewed literature reveals that cooling demand is increasing in Europe. District Cooling Systems (DCS) are provided to fulfil this demand. However, DCS has challenges including the low temperature difference between the supply and return water. Thus, the specific challenges inherent to DCS require specific modelling, simulation, and control methods for efficient and green operation of DCS. In this paper, we study the modelling, simulation, and control of DCS. The DCS is composed of the generation, distribution, and consumption sites; while each of these sites are partly responsible for DCS energy consumption and CO_2 emissions. Our purpose is to critically review the current practice in DCS to distinguish the gaps in the energy-efficient operation of DCS. We then review the control methods applied in DCS, particularly the control of consumption and generation sites, to identify the technique that best applies to a whole implementation of modelling and predictive control in real-life applications of DCS. Modelling and control of DCS are proved to be satisfied through tools and methods like Modelica and predictive controllers. The gaps identified in this paper are the path towards the development of an integrated tool for efficient and green operation of DCS.

Keywords: Energy Efficiency, District Cooling Systems (DCS), Modelica, Model Predictive Control (MPC), Literature Review, Green Operation, CO_2 emissions.

1 INTRODUCTION

An assessment of the cost of air conditioning in buildings shows that the energy consumption is growing in Europe in the last decades [1]. The studies on energy efficiency reveals that 40% of total energy consumption in Europe is in the buildings [2]. These buildings also contribute to 36% of carbon dioxide emission in the European Union [2]. Many research have been conducted to construct and maintain energy efficient buildings [3],[4]. A main goal of the existing research is to reduce the greenhouse gas emissions [5], enhance thermal comfort in buildings, increase indoor air quality [6], and reduce energy consumption in any form. A significant part of this energy consumption is in the District Cooling Systems (DCS) [7]. The DCS has been pointed out by the EU Energy Efficiency Directive (EED) [8] as one of the significant pillars for accomplishing the energy efficiency goal of reducing primary energy consumption by 20% [2]. Therefore, it is essential to integrate the new technologies into DCS to obtain a higher efficiency compared to what we already have.

Rezaie et al [9] review district energy systems and its why and wherefores from different points of view i.e. environmental, economic, technical, and government policies. A critical point of this study is the size of the district; It is mentioned that district energy systems are beneficial to large public buildings and have come into consideration for their high efficiency and economical costs in the districts [10]. Gang et al [11] perform a review of DCS including the history of DCS, optimization and planning, and integration of DCS with renewable energies

In this article, we would like to integrate the latest control technologies like Model Predictive Control (MPC) [12] into DCS [4]. As these model-based controllers rely on the dynamic model of the system, we need to review the literature on the developed models, modelling, and simulation of DCS. Later, we study and review the control methodologies in DCS for the efficient and economical operation of DCS. At the end, we focus on the literature that combines both model development and control methods and identify the future direction of DCS technologies. We review the existing literature on modelling, simulation, and control of DCS. Our purpose is to study the literature *critically* and *systematically* to find the gap in the current practice of *modelling and control of DCS*. Finding this gap provides us with the further research direction to find solutions on optimal performance and operation of DCS.

1.1 Components of DCS

The DCS is composed of generation, distribution, and consumption sites. Generation is the site where chilled water is produced in chillers and the heat is rejected through cooling towers. The chilled water is then carried to the distribution system and through the pipelines to the consumption site and end-users. The consumption site consists of the Heating, Ventilation, and Air-Conditioning (HVAC) equipment in the buildings.

1.2 Challenges of DCS

Most of the research to date has been conducted around the energy efficiency and efficient power generation in District Heating Systems (DHS), while there is a gap in the DCS technologies in the literature. The main challenge in DCS compared to DHS is the *low temperature differentials* between the supply and return water. This difference is around 8°C (supply at 4°C approximately and return at 12°C approximately), while in DHS, this difference is usually greater than 40°C. The cost of pumping, the piping system, the consumption, and end-user equipment also grows because these low differentials require higher mass flow rate to remove the required heat. Maximizing the temperature difference is mentioned as the key to the quick growing of DCS and the energy efficiency in DCS regardless of the type of the distribution system [13]. This requires efficient modelling and control techniques of the generation and consumption equipment.

In practice, DCS has several advantages, e.g. lowering greenhouse gas emissions [5], reducing the operation and maintenance cost, and the space requirements of generation system by centralizing the equipment for the whole district; Improving the balance on energy peaks and regulating demand capacity [14]. In addition, developing the DCS technology also reduce the transportation costs as the combustion system is at a central location and there is no need to transport the fuel to the end users. The peak load time planning in DCS generation and storage can lead to 27% energy efficiency in the scale of a city like Hong Kong [15]. Gang et al [11] review the history of DCS, optimization and planning, and integration of DCS with renewable energies. The future work of [11] suggests a gap in the *optimal performance* of DCS.

2 WHAT IS THE CURRENT PRACTICE?

In this part, we specify the research questions to approach this problem. The leading questions are:

1. What are the current modelling and control approaches in optimal operation of DCS?
2. How is the connection between modelling and control?
3. How does the integration of modelling and control effect the energy efficiency?
4. What is the current development & literature on the model-based control specifically MPC?

To answer these questions, we perform a systematic literature review. To find the related literature, the keywords “District Cooling” AND “Model” OR “Modelling” have been searched in data bases ScienceDirect, IEEE, Web-of-Science, Scopus; The number of existing papers starting from year 1990 to March 2018 have been illustrated in Figure 1. In Figure 2, the number of publications including the keywords “District Cooling” AND “control” in either their title or abstract in the abovementioned databases is depicted.

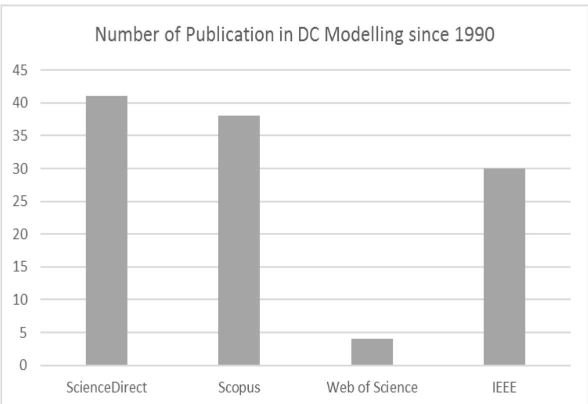

Figure 1. Publications in DC modelling

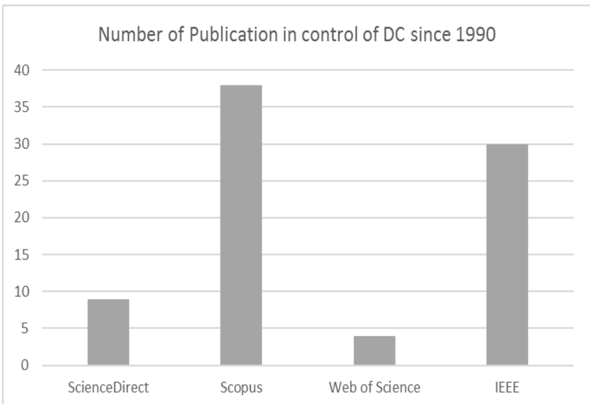

Figure 2. Publications in DC control

The year 1990 is particularly interesting for us as two major incidents happened; First, the air-conditioning systems and energy policy management have been widely changed after the 1970s energy crisis and the oil price increase in 1990s. Second, the advancements in MPC in the industry happened during the late 1980s. Thus, 1990 is the time of the introduction of MPC in the energy industry.

3 MODELLING AND MODEL DEVELOPMENT

In this section, we review the literature on the modelling of the components of the DCS. Bacher et al [16] identify models for the heat dynamics of buildings in the form of dynamic equations. These models are based on both the physical knowledge of the system and the measurement data. The complexity of the model can also be tuned based on the statistical significance of the model compared to the real data. Another area that has been studied is the load calculation and demand management in DCS. The review of the DCS in the introduction of [17] confirms the lack of literature in optimizing the operation of DCS. In a similar research, DCS temperature differentials and optimization of ΔT is considered [18]. The main discussion of [18] is the economic benefits of optimizing the temperature differentials based on the time of the year.

3.1 Model Implementation and Simulation

After choosing the dynamic model equations, the next step is to simulate the equations in computer programs.

Simulation Software and Platforms

Various tools exist to simulate the energy system depending on the purpose of the developer, such as EnergyPlus [19], Modelica [20]. Furthermore, the data exchange and the integration of models of dynamic systems have been performed by Functional Mock-up Interfaces (FMI) standards [21]. FMI is a tool to standardise data exchange and model integration among simulation software packages. An Overview of different platforms and tools of energy system simulation is given in Table 1.

Table 1: Buildings and energy systems simulation tools

Modelling software	**Main features**
Ansys	Design analysis and modelling, advanced computation tools
Energy Plus	Energy load simulation, well-linked to other simulation environments, simulation of the lighting/heating/weather data related to the buildings
MATLAB/SIMULINK	Dynamic system analysis and control tools, Computation, and optimization tools available
Modelica	Explicit simulation of complex dynamical equations, component-based graphical interface, ability to integrate the models with control systems

Below, we exploit the features and applications of Modelica in the literature of energy systems simulations to show its effectiveness in DCS simulation.

Modelica and its libraries

Modelica is an object-oriented, open source, equation-based language to model dynamical systems. It has become one of the key tools used in modelling and simulation of energy systems and buildings for energy analysis, thermal load calculation and control design. The main benefit of Modelica which makes it easy and accessible to use is that it is open source, freely available and non-proprietary. Modelica library developers have written various libraries on building and thermodynamic systems modelling which can be used to model the HVAC systems of a building; examples are heat transfer and solid materials thermal modelling library, building Systems library, Buildings, Annex 60 library for simulation of building and community energy systems [22]. This is all because Modelica designed to support effective library development and model exchange among various environments. To this purpose, Functional Mock-up Interfaces (FMI) also facilitate the exchanges between Modelica and other simulation environments.

Model Validation and Calibration

Following the simulation of the dynamic model of DCS in the suitable simulation program, we need to calibrate the model parameters based on the real data and validate the performance of the model through simulations. Werner [23] describes the lack of validated and trustworthy data on European cooling systems and demand, and as a remedy, provides data on recent cooling demands in Europe based on the aggregated data from different countries. This information about the demand site can be used in strategic management and planning of our DCS and validation and calibration of the models. Gang et al [24] proposed a design methodology for DCS that considers uncertainty in the DCS variables such as load, weather data, and demand. The method then deliberates an optimized design of the DCS. The results are of the case study in Hong Kong show that DCS can be modelled in size and configuration against the uncertainty analysis.

4 DISTRICT COOLING CONTROL

There exists an extensive literature on the planning, management, and control of DCS in different levels. In this section, we would like to distinguish our focus on the control design with a dynamic system i.e. input/model/output point-of-view. Although research has been done in the area of optimal management of DCS [25], we focus on control design at a component level rather than management, planning, or supervisory from a higher level. The DHS have been well studied in the literature [26]–[29]. Modelling and operation of DHC in [30] provides a comprehensive dynamic model of a small-scale DHCS based on their physical models and operations. This paper can be used as a start to solve the problem of DCS in a large scale. The models are simplified to describe heat exchanges in linear equation dynamics. However, the simplifying assumptions that all the buildings have the same supply water temperature, or the heating capacity takes away the challenge of district cooling. We learn the exchangeable ideas between DHS and DCS [31] and focus on the challenges of control of DCS. In the next subsections, we review the literature on the two main sites of DCS where control algorithms are needed.

Damien et al [32] present the Modelica simulations and model validation of the cooling system of the east of Paris. The paper is a case study of the application of Modelica in modelling DCS and the validation of the identified model using real data. These results can be beneficial in our case study evaluation; however, the authors don't discuss the control techniques of DCS in [32]. In [33], the state estimation and MPC of a building zone air-conditioning system has been studied. The building zone is modelled in Modelica using a so-called "*Resistance-Capacitance (RC)*" model of a zone in the building [34]. This model is then used as an "*emulator"* which is validated using the measurements data from the building. This validated model is now ready to serve as the basis for model-based control. The objective of the modelling and control is to have more efficient buildings i.e. less energy consumption and costs, and higher level of comfort. These factors have been considered in the "*objective function*" of the MPC problem in [33].

The chillers and cooling towers in the generation site of a DCS consume a considerable amount of energy to produce chilled water for the district [35]. In [36], the authors introduce a method to deliver constant flow rate temperature difference in the DC network based on the cooling load calculations. The result is that the efficiency of the chilled water distribution can be improved by adjusting the temperature difference flow rate in the central cooling network. Y. Ma et al provide and validate the models of chillers, storage tanks, fan coils, and the building load model; then design a model predictive controller which considers the constraints of the system [37]. The objective of the control problem is to *minimize the electricity bills and maximize the plant efficiency*. The focus of this paper is on the modelling and control of the generation and distribution sites which is mainly storage units and tanks. The article [4] is an extended work of the previous authors in which they improve the results by incorporating the chillers and cooling towers models and introducing a terminal constraint for the stability analysis of the MPC solutions. However, the models are still at a very simple stage while proved to work in the application of the algorithm in the office buildings of the case study.

5 CONCLUSIONS

This paper is a review on the modelling and control of DCS. This review is performed systematically and with a focus to find the gap in the modelling and control methodology of DCS. Here are some findings of this review:

- We extended the review in [11] with a focus on modelling platforms and software and control theory techniques.
- This review is beneficial to expand the work in [4] in terms of modelling the components of DCS and developing advanced MPC theory for district energy systems.
- The **main challenge** in DCS is **low temperature differences (ΔT)** between the supply and return water (around 8°C - supply at 4°C and return at 12°C approximately). This challenge makes many developed methods in DHS inapplicable in DCS.
- Many reviewed articles focused on either modelling or operation optimization of DCS. There is a lack of **connection between the modelling and control of DCS**: How the details and methods of modelling affect the control performance and energy efficiency of the overall system?

- DCS Generation: As the main components of DCS, chillers consume large percentage of energy. The cooling water pumps, cooling towers, and the thermal storage systems and their coordination with chiller plants need further study.
- An **integrated tool to model and control the DCS**, FMIs combine the different software and platforms in dynamic simulation and implementation.
- Modelica offers to be the ideal language to model DCS and to integrate the models into the management, optimization, and control levels.
- A gap exists in **applying the theories of MPC in practice and real-life application of DCS.** Although MPC is a developed technology among control theory researchers, there is still a gap in applying MPC theories in energy systems like DCS.

In future, we aim at modelling the DCS and developing a simulation tool based on Modelica language that provides reliable models for model predictive controllers. In this way, we will build an integrated tool for modelling and control of DCS.

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