Refrigeration Analysis of Ball Arena

MEGN 461 Final Report

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Table of Contents

Abstract

Ball Arena is home to numerous sporting events in Colorado. During the hosting of these events, it is important to consider the HVAC demands necessary to provide adequate cooling and air circulation to a crowd of 21,000 fans. Our team analyzes the refrigeration demand and cost associated with running the facility, taking both air conditioning and ice rink refrigeration into account as the two main refrigeration challenges. The result of analyzing the stadium is that there is no reason to improve the chillers used in the HVAC system. Out of all of the costs involved with the operation of the arena, the HVAC is minor. The only reason to replace key systems would be due to malfunction, damage, or age.

Introduction

Ball Arena is a multi-purpose indoor arena located in Denver, Colorado. The facility hosts various events throughout the year, including notable professional Colorado teams such as the Denver Nuggets, Colorado Avalanche, and Colorado Mammoth. As a large public facility, the arena's heating, ventilation, air conditioning, and refrigeration (HVAC/R) systems play a vital role in maintaining indoor air quality and ensuring the comfort and safety of occupants. In this report, we present a detailed analysis of the HVAC/R systems in Ball Arena, focusing on their design, operation, performance, and optimization pathways. Our goal is to identify potential areas for improvement and recommend strategies to improve energy efficiency and minimize operational costs without compromising air quality. This report is intended to serve as a reference for facility managers and engineers looking to improve their existing air conditioning and refrigeration systems specifically for ice hockey events sponsored by the National Hockey League (NHL).

Subsystem Exploration

As a first step in understanding the complex systems at play in large-scale HVAC systems for ice arenas, a key first step is to differentiate between the systems at play. The two primary systems for HVAC/R analysis of large stadiums is the Centralized Air Conditioning and Ice Rink Refrigeration. For stadiums that do not include ice rink systems, the ladder can be neglected in cost and energy analysis.

Air Conditioning

The HVAC systems in place at Ball Arena are exceptionally complicated, and doing a complete analysis is beyond the scope of this report. However, by analyzing the main components of the system we can get a rough understanding of the energy requirements associated with the operation of the stadium. After interviewing Jerry Vanyo, an employee with Trane Technologies, we found that the primary chiller used to refrigerate the stadium is the CTV - Agility®

Centrifugal Water-Cooled Chiller. Four of these chillers are used in a consolidated location to cool the air that circulates throughout the stadium. The capacity of these chillers is 450 Tons each [1], and service a throughput of 724,000 CFM. Conditioned air is distributed via 12 Air Control Units (ACU) and transported by 735,000 pounds of ductwork [2]. Considering these metrics, it can be concluded that the stadium has a maximum cooling capacity of 1800 tons, which will be used in the modeling analysis.

Ice Rink

The main stage of hockey events requires a substantial amount of refrigeration and energy to maintain the ice at NHL standards. This refrigeration effort consists of chillers, compressors, condensers, brine, and intricate radiation loops for brine and refrigerants. The team decided to ignore the energy cost of the ice rink provided this poses another Thermodynamic investigation, which is outside this report's scope. However, the rink does still impact the air and resultant HVAC demand and is considered within the modeling process. For a brief overview of the thermodynamic details of ice rinks, and how to model one, check Appendix A.

System Analysis

To define a control for analysis, we decided to look at the operating expenses for hosting a full stadium for the duration of a professional hockey game. The dependent variables for consideration when modeling this event include energy consumption and cost of operation which are proportionally related. The independent variables for the experiment are listed in the Noteworthy Variables section, which includes temperature, humidity, stadium occupancy, and energy cost data for the Denver area.

Noteworthy Variables when Modeling

The key parameters when modeling the HVAC requirements for Ball Arena were primarily temperature and humidity data. Specifically, we examined the operational costs associated with hosting a game over a one-year period. Looking at the weather data sourced from the Visual Crossing API [3] to track temperature and humidity levels for every day of 2022. Given that the NHL regular season runs from October to April, our analysis includes data from the tail end of the 2021/22 season and the start of the 2022/23 season. This is highlighted in the figures produced in the results section.

Another important variable we looked into modeling given the weather data was how stadium occupancy impacts the refrigeration requirements necessary for hosting a game. Specifically, given a distribution of attendee count, we looked into how the cost of refrigeration during a game changed. The reason the attendee count is pertinent to this analysis is that people emit both heat and humidity through perspiration. The estimated values for attendees were a heat emission of

104.76W [8] and a perspiration rate of 16.7g/hr into the air [6]. Furthermore, players were determined to have a heat output of 1000 W and sweat at 3-4 Litres per hour [7]. Provided that sweat is 99% water, we assumed that perspired sweat is entirely water in the atmosphere.

The energy requirements calculated given this data, and assumptions made in the preceding section, were converted to a direct cost basis. This was done using the average cost of electricity for 2022, which was calculated using the data from St.Louis FRED economic data. Exploring this data indicates an average price of ~ $0.154 per kWh [4] for 2022.

Assumptions

Throughout the process of research and solving of our problem we found some issues in the data that we were able to gather and because of this we needed to make some assumptions for a solution to be possible. Some assumptions were made throughout the whole process. Overarching assumptions were the most important and most impactful such that we could progress through the project and get useful information from our analysis.

The most important assumptions that were made were about the game and conditions that must be maintained during and slightly before the game. A basic game was chosen to be modeled, the game consists of 3 hours of total time including pregame warmup and aftergame wrap-up during which the arena must be kept at the desired temperature of 63∘F with a relative humidity of 35% [10]. We assumed that the ice rink had already been frozen and is in operational condition of 22∘F, before the start of this time [10]. While this assumption means a large portion of the cost of running a game is excluded, we wanted to focus on the HVAC system itself with an analysis of the ice rink being a secondary goal that would give some more insight into how much the HVAC system must work to maintain the desired atmospheric conditions. Note that in actual game hosting, stadiums have to remake the entire ice rink per game which adds to the refrigeration costs [11].

Analysis of heat transfer of the ice rink itself had to have a large amount of assumptions being made to create a model with the data that was available to us. One such assumption was the size of the arena which is not readily available data. To determine the dimensions of the arena we took known quantities, being the size of the rink, and scaled that to the full size of the arena given models and images publicly available. These assumptions lead to values that are not perfect but are within an order of magnitude of the actual values and provide a good estimate to the required HVAC system. These dimensions end up being approximately 600 feet wide by 1000 feet long by ~70 feet tall. The height is the worst estimate that we have as it was nearly impossible to find a good enough analog to determine the actual height. The other dimensions are relatively close given the images and data that could be collected online based on the standard NHL hockey rink size of 85 feet wide by 200 feet long. Another assumption being made is how the air interacts with the ice and generates convection of energy. To get an estimate of heat loss to the ice we assumed a constant sheet of air that would spread across the ice rink in a uniform turbulent manner as a base value. To determine the actual estimated airspeed near the surface of the ice we decided to use an adjustment factor that multiplies the simple estimate for the air speed across the whole arena which accounts for the open area and the large amount of movement that occurs on the ice due to the players that skate around the rink. We also assumed that the convection transfer across the whole of the surface was constant even though some areas would certainly have different local heat transfers due to ice and local air conditions.

The last area where some assumptions had to be made is in the actual HVAC analysis itself. Much less had to be made in this area than the previous analysis discussed simply because we have the most data available for the system with the most useful data to be used in modeling the arena during a standard NHL game. The first major assumption that is being made is about the starting conditions of the arena, which we assumed was to already be at the desired temperature and must simply take outside fresh air that meets the required conditions in the arena. To do this we must also assume that the air will naturally be mixed thoroughly to prevent any spaces from stagnant air. This assumption is fairly good considering the large capacity and speed at which air is pumped into the system, along with the tall ceiling leads to ideal situations in which the air that is heating up will naturally rise into the areas in which the conditioned air will be pumped into the arena. Another assumption being made is that the people and ice both generate water and heat transfer at fixed rates that do not vary over time or location, meaning that it would all be equally dispersed throughout the arena immediately which is a big assumption to make but can be seen as something that can model what we are looking for accurately enough for the rough estimates. The biggest assumption being made however is that the system must immediately have complete access to any water in the air and be able to add and remove it even after having been pumped into the building since we are including the water released from the occupants. While this is not very realistic, it could be handled through more recycled air flow such that we can remove extra water or add more water if needed after the consideration of the impact of the people and rink on the total humidity in the arena.

Modeling

We opted to use Python with the inclusion of numerous libraries to build a preliminary model of the problem. The model is written in a Python Jupyter Notebook, which is a file type that lends itself well to academic studies and the repeatability of results. We strongly encourage readers to use the notebook linked here as well as pasted in the Appendix as a supplement to understanding the detailed modeling process. Only highlights of the process and a general overview will be covered in this section. Given the scope, we were able to break down the modeling process into the following:

Setup

Load dependencies for the project, including matplotlib, a plotting tool; psychrolib, a python psychrometric data library; pyromat, a thermodynamic library; pyfluids, a fluids data library; ht, a SciPy dependency used for heat transfer calculations; math; and pandas, a common data frame toolkit.

Define Thermodynamic Functions

Define preliminary functions used to convert units, such as °F to °C. More importantly, define functions used for conducting thermodynamic calculations. These functions use the following equations in their implementation:

$$\omega = \frac{m_v}{m_a} = \frac{M_v}{M_a} * \frac{p_v}{p_a} = 0.622 * \frac{p_v}{p - p_v}$$

Equation 1*: Specific Humidity equation*

$$p_v = RH * p_{sat}$$

Equation 2*: Water vapor pressure equation*

$$p_a = p - p_v$$

Equation 3*: Dry air pressure equation*

$$\dot{m}_{da} = \frac{\dot{V}}{v_{air} + \omega * v_{vapor}}$$

Equation 4*: Mass flow rate of Dry Air*

$$\dot{m}_v = \frac{\dot{V}}{v_{vapor} + v_{air}/\omega}$$

Equation 5*: Mass flow rate of Vapor*

$$\dot{Q}_{HVAC} = \dot{h}_{out} - \dot{h}_{in} - \dot{Q}_{people} + \dot{Q}_{ice}$$

Equation 6*: Net HVAC cooling required*

$$\dot{Q}_{electric} = \dot{Q}_{HVAC}/COP$$

***Equation** 7: Net electricity for cooling required*

Define Key Variables

Defining notable variables for Ball Arena and game conditions, these variables include a game length of 3 hours [10], NHL standards of 35% RH and 63 °F [10], and an atmospheric pressure of 84 kPa [12]. Furthermore, the arena variables include estimated dimensions for volume, arena occupancy, attendee and athlete heat generation, and energy costs for Denvers. Finally, HVAC variables were defined including energy efficiencies and volumetric flow rate.

HVAC Analysis

Define a method to run an analysis on the system, taking into consideration the heat generation and transfer of the ice, attendees, players, and weather conditions. Repeat this analysis for every day of 2022, taking the average temperature as the changing parameter for the day. This serves as the primary data used in the report.

Plot Data

Plot the defining metrics using MatPlotLib, which will cover energy requirements and cost requirements across the entire year. Print out the estimated operational cost for the entire year.

Further Exploration

Perform exploratory data analysis to look into the impact of occupancy on HVAC cost. Explore the future forecast in Denver to determine the HVAC cost of hosting a game over the next two weeks. Look into the efficacy of replacing the current chillers with new, updated chillers that have better performance coefficients (COP).

Results

The analysis considered a range of factors including occupancy, system efficiency, weather data, and predicted costs to assess the effectiveness and sustainability of the HVAC system. We utilized a variety of data visualization techniques to present the results, including plots of cost over time for the entire year, as well as daily operational costs associated with hosting a game. These results are intended to inform decision-making around HVAC system improvements at Ball Arena and provide insights that can be applied to similar facilities.

Observing the heat refrigeration requirements for air in Ball Arena with 18000 attendees indicated large variations depending on local weather conditions. For example, on the coldest day of the year, we estimate that the heat removal requirement would be 525 tons. This is a stark contrast to the hot summer months of July and August where this operational cost would be in the range of 850 tons, reflecting an almost 62% increase in cooling requirement due to weather alone. These findings are visualized in Figure 1. Note that the highlighted region in all graphs represents the typical NHL regular season for which a stadium owner would expect to host professional hockey games.

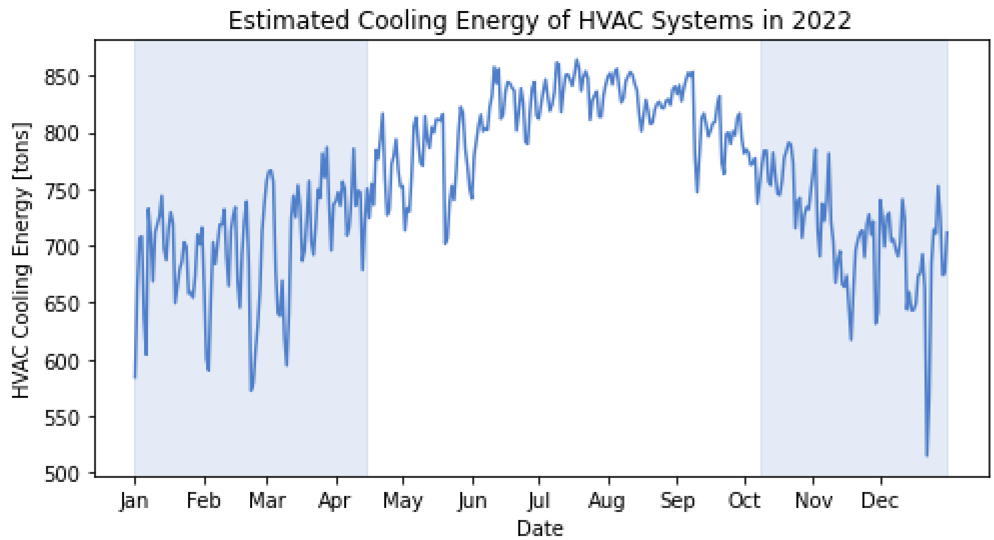

Figure 1*: Heat Energy Pulled from HVAC Operation for a 3-Hour Game Across 2022*

Translating the cooling requirement into meaningful data, we can see that the energy consumption required to facilitate this cooling requirement is plotted in Figure 2, and the cost for running these systems (energy basis) is shown in Figure 3.

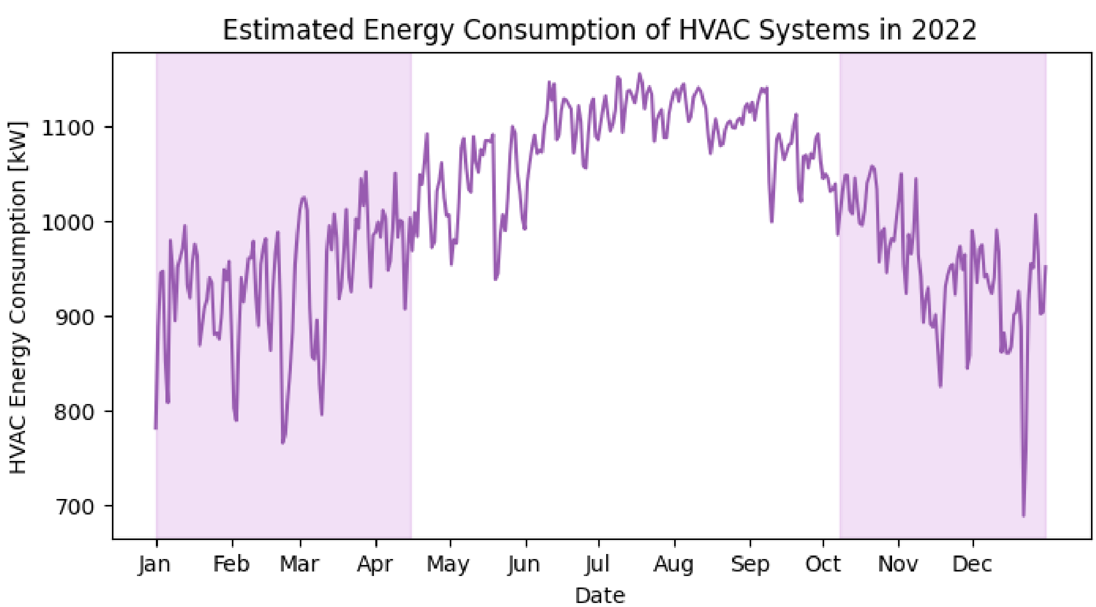

Figure 2*: Electrical Requirements for Running HVAC Systems Across 2022*

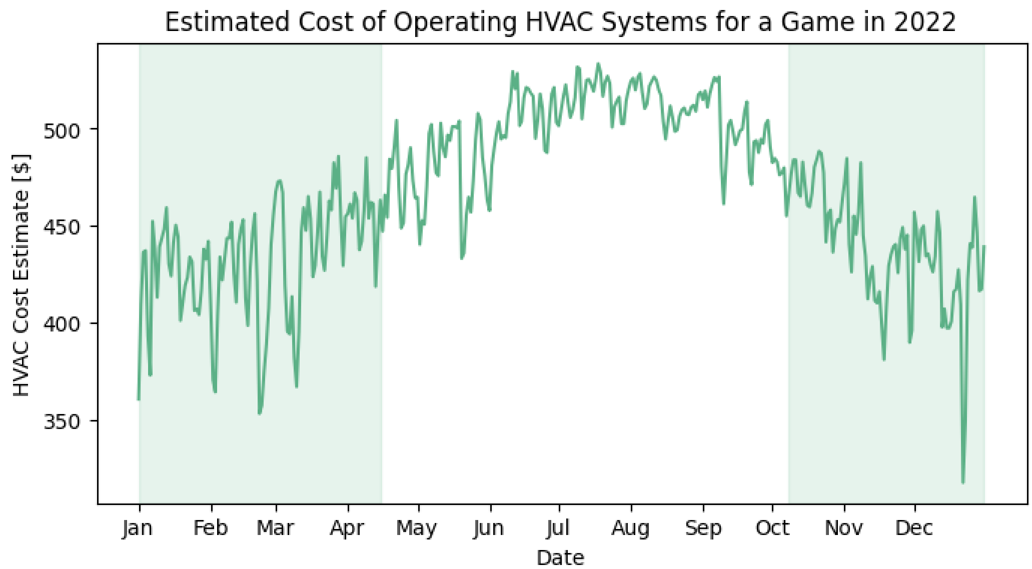

Figure 3*: Cost of HVAC Operation for a 3-Hour Game Across 2022*

These findings indicate that, as expected, the cooling costs for large stadiums like Ball Arena increased 50-60% during the summer season. Additionally, energy prices can also be expected to increase during this time, depending on the year and location of the stadium - further impacting the problem at hand. Through our analysis, our team predicts that the price of running HVAC systems while hosting a game will cost around \$400 to \$450. Exploring factors that impact this metric, our team found that the largest contributor to raising this price was the number of occupants. A visualization of this relationship is shown in Figure 4, which depicts about a \$0.025 per attendee relationship. This linear relationship is intuitive, provided an assumed constant heat generation rate per attendee will directly impact the cooling requirements of the building.

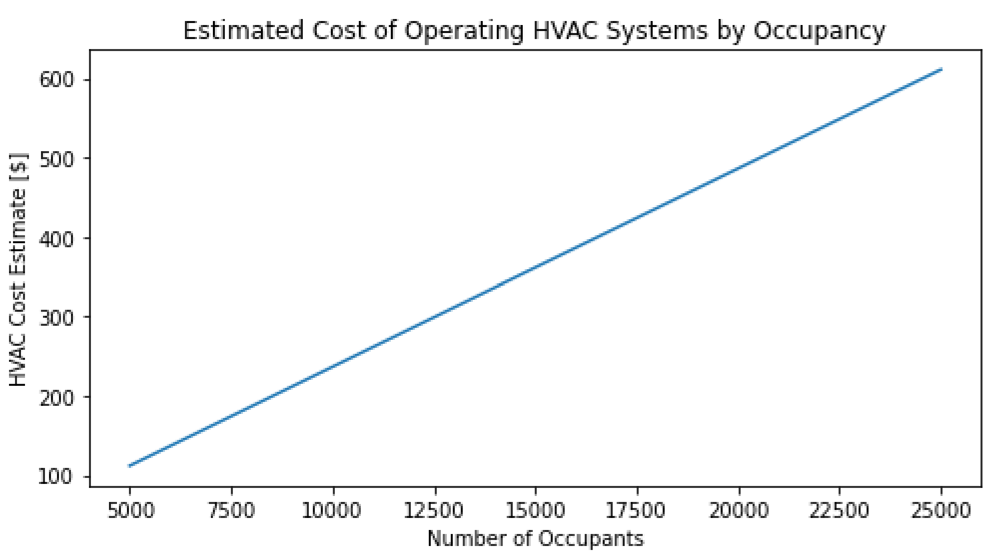

Figure 4*: Relationship Between Stadium Attendance and HVAC Cost for 3 hours (game length)*

Given the valuable toolset created, we decided to look at how we could use this modeling tool to predict operational costs given future weather conditions. This serves as an extension to the existing analysis and uses current, relevant, data. The results of running a forecast on Sunday Apr 30, 2023 is depicted in Figure 5. Note that this result employs the same methods used to calculate the former results. As shown, the cost of operation is approaching higher-than-average levels for the NHL season within the next two weeks.

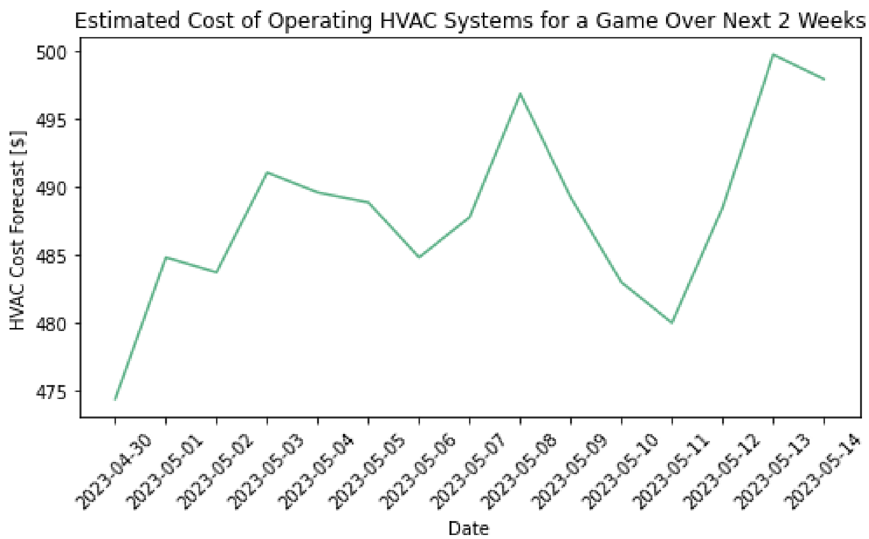

Figure 5: *Forecasted Cost of Operation for Hosting 3-Hour Game*

As a final part of data exploration within the scope of this project, we wanted to look into the value of replacing these chillers with more efficient units. For this, we assumed that the new COP would be a 92.6% improvement over existing systems. These results are plotted in Figure 6.

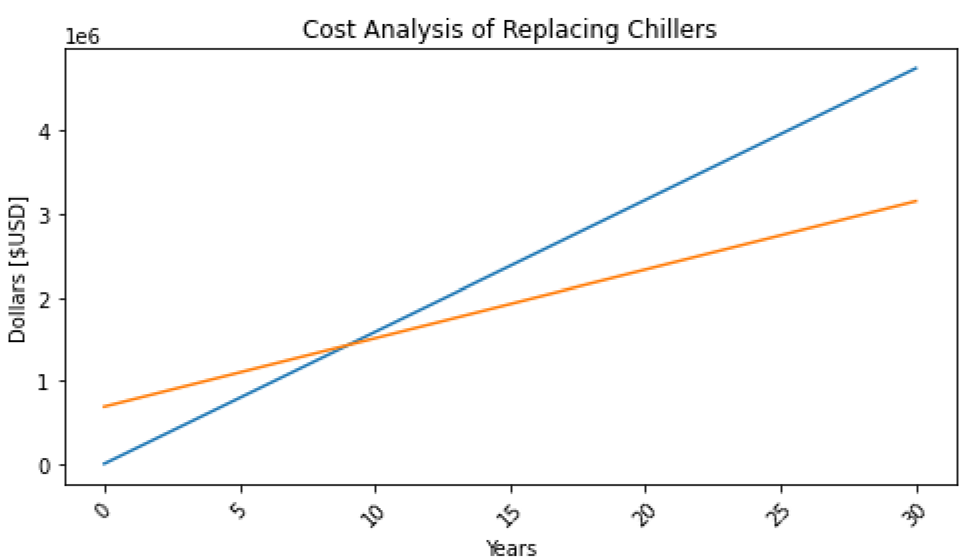

Figure 6: *Cost analysis of Replacing Chillers over 30 Year Timespan*

Conclusion

The group determined that the operating cost for running the HVAC system is relatively low when compared to running other systems such as brine pumps & fans, compressors, ice-surface lighting, interior lighting, dehumidification, and other building systems (concessions, outdoor lights, locker rooms, etc.). From the assumptions made, the analysis reflects that the operating cost of the CTV Chillers is proportional to the number of people in attendance. The analysis neglects heat loss occurring out of the building, and any possible ductwork inefficiencies. These are factors that could improve the accuracy of the analysis if further looked into. Different locations that offer various humidity levels, air pressures, and differing energy costs are areas of exploration the team believes would improve the validity of the analysis. Investigating any possible offsets to energy consumption such as improvements from renewable energy. Next, expanding the energy consumption analysis to include draws from the air distribution subsystem, would provide a more complete picture of the overall building's system performance. According to the cost analysis of replacing chillers, the yearly cost savings are directly reflected by the upgraded coefficient of performance brought by the new chillers.

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Appendix

Appendix A - Ice Rink Analysis

The construction of a typical ice rink surface is depicted in Figure A-I, and includes layers of ice, chilled concrete, insulation, heated concrete, and a base with a drain.

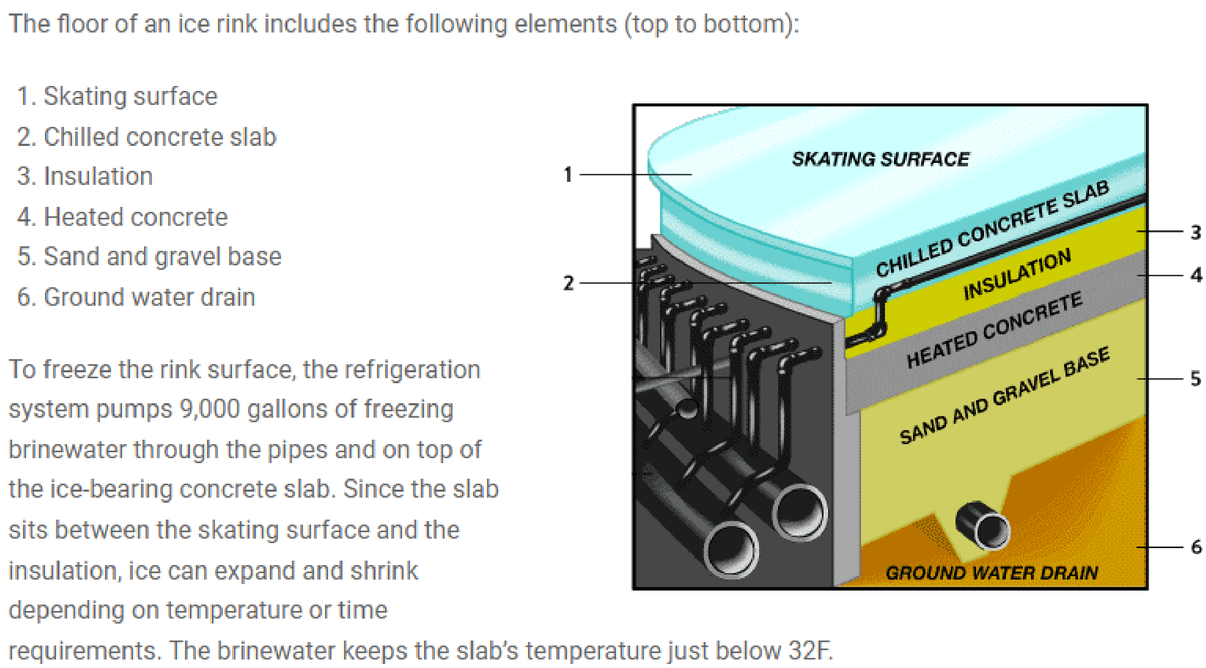

Figure A-I: *Typical Ice Rink Lamination [11]*

The physical skating surface is required to be ~22 °F as per NHL regulations [10]. The 5" thick chilled concrete slab is typically chilled using ~190 tubes carrying Brinewater (CaCl + H_2O at 21% by mass) or glycol. Glycol is slightly less effective at transferring heat, and is about $18,000 more expensive to install [13]. The tradeoff occurs when considering the corrosive properties of Calcium Chloride will wear out a rink's plumbing in 15-20 years, whereas Glycol can last over 30 years showing minimal hardware damage [13]. The insulation is about 4" thick, with a small vapor barrier on top to allow for pressure escape given thermal fluctuations [15]. Under this is a 12" thick heated concrete slab which is used to prevent the ground from freezing. The slab is heated using a mixture of Water and Ethlyne Glycol (20% H_2O) [15]. The floor temperatures are maintained using chillers (heat exchangers) in an indirect refrigeration cycle, depicted in Figure A-I.

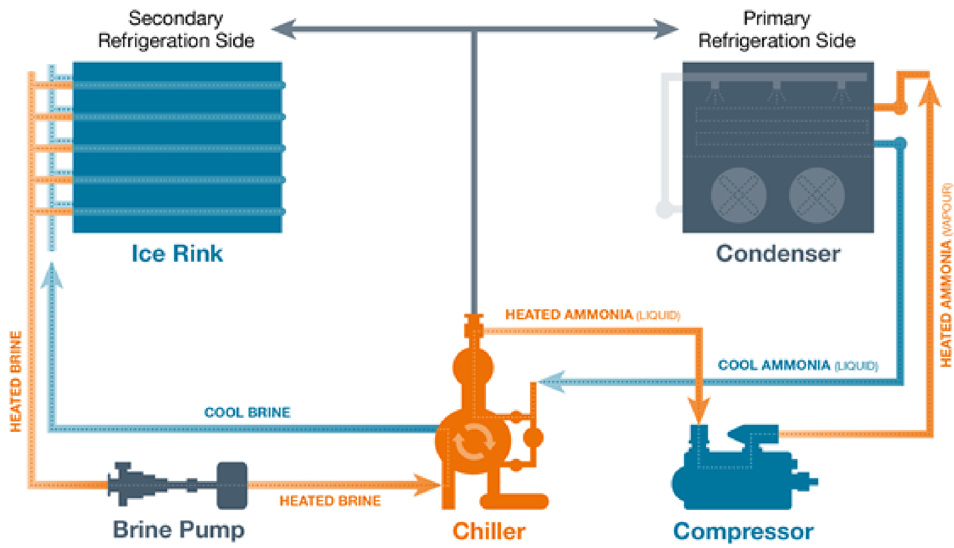

Figure x: *Refrigeration Loop for Typical Ice Rink [14]*

As depicted in the figure, the primary refrigerant that cools the brine is liquid ammonia; however, more common coolants include Hydrofluorocarbons (HFCs) and Hydrochlorofluorocarbons (HCFCs). Developments from the Environmental Protection Agency (EPA) in the past decade have led to the adoption of more eco–friendly refrigerants, meaning that common refrigerants like R22 (HCFC-22) are being phased out and replaced with R-134a and R-513A. These HFCs are being used given they have a lower Global Warming Potential (GWP), which is the measure of how much a given mass of greenhouse gas is estimated to contribute to global warming relative to the same mass of carbon dioxide

Investigating the specific refrigeration systems in Ball Arena, we were able to determine that the chillers used included 3 RTHD - Optimus™ water-cooled helical rotary chillers for keeping the ice frozen. These chillers were installed in 2011, and are currently running at a capacity of 103.5 Tons which was obtained from an interview. It is worth comparing this to the capacity of newer models that range from 125 - 400 Tons [16], such as the 200-ton models that were installed in the San Jose SAP center in 2021 [17]. The primary refrigerant used in these systems is R-514A, and we will assume that an ethylene glycol solution of 80% is used for transferring heat from the ice to the chiller, as well as heating the concrete base.

Appendix B - Python Jupyter Notebook

GitHub code listed here: https://github.com/DominickBeaman/thermoproject/tree/main