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COST OF OWNERSHIP ANALYSIS OF AN HVAC SYSTEM

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OF AN HVAC SYSTEM

by

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ABSTRACT

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OF AN HVAC SYSTEM

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A private owner has decided to build a new 17,500 square foot document storage and archive center in Mumbai, India. This facility will store rare documents, books, manuscripts, photos, and audio recordings in a manner to ensure the preservation of historical items. The center will be open to the public, Monday through Saturday from 8:00 – 18:00. The project is to design an HVAC system for the archives center. HVAC, named for Heating Ventilation and Air Conditioning, is a compound system which involves a system of fluid exchange to allow the closed surface to regulate its internal temperature for comfortable living and working regardless of external weather conditions. A HVAC system aims to provide thermal comfort and indoor comfort, which is designed using the principles of thermodynamics, fluid mechanics and heat transfer. The constant recirculation of air inside the building to keep the air flowing around pure and maintain the temperature in the range which will ensure the relative humidity in comfort zone which

varies along with the weather conditions and location. The goal of this paper is to dive into the cost analysis of the HVAC systems that best utilizes space, uses the latest technologies, and provide quality indoor environment per the requirements in the competition guidelines. This report summarizes total cost of ownership the client would have to pay out of his pocket before, during and after the installations of systems recommended by the design engineer.

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CHAPTER 1

INTRODUCTION

The teamed portion of this project simulates what an engineering consulting company would do when approached by a client with specific requirements. The client wants to build a new document storage and archive center in Mumbai, India, which can store rare documents, old recordings and other historically significant readings without depleting their structural as well as informational integrity, that means the building should keep them within certain pre-specified temperature, humidified and ventilated conditions. The project endeavors to design the HVAC system that meets those requirements. The archive center, among other things, also contains lecture halls, library, and offices, all of which have different condition requirements because of their different purposes. This project is a part of annual competition organized by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) that recognizes the outstanding student design projects at the 2021 ASHRAE Winter Meeting scheduled for January in Chicago, Illinois.

1.1 HVAC

HVAC, named for Heating Ventilation and Air Conditioning, is a compound system which requires a system of fluid exchange to allow the closed structure to regulate its internal temperature for comfortable living and working regardless of external weather conditions. A HVAC system aims to provide thermal comfort and indoor comfort, which is designed using the principles of thermodynamics, fluid mechanics and heat transfer. This involves a constant recirculation of air in order to maintain the temperature and relative humidity in the range of comfort zone which varies along with the weather conditions and location. The objective is to design an HVAC system that best utilizes space, uses the latest technologies, and provide quality indoor environment per the requirements in the competition guidelines.

1.2 Steps Involved in the Design Process

Each HVAC system design and the project requirements are unique, and it needs a personalized analysis and methodology. To determine the qualities and type of control system to be used in the HVAC system, the size, weather around the structure, operational parameters, financial limitations and other preferences or goals of the building owner must be clearly defined before the start of the project. There is never only one final answer as might be in other engineering applications, and to select a high-functioning HVAC system which can select the optimal options a HVAC system selection matrix is employed, as shown in Table 1.1. This matrix can be used to organize and easily convey all the collected information to anyone interested in the process.

But before filling the information in this matrix, there are four phases that have to be carried out by the design engineer, namely:

1.2.1 Gather Information

This phase of the HVAC design process is where the design engineer clearly defines the project parameters using the competition guidelines and ASHRAE handbooks. These factors include, but are not limited to initial cost, operating cost, maintenance cost, maintenance requirements, energy efficiency, redundancy, acoustics, equipment space, transportation requirements, occupant comfort, etc. This started with the guideline from owner and then is formulated according to established local and international rules as well as current trend. This step included calculating the heating loads inside the building which would later be adjusted to required condition by the final selected HVAC system after installation.

1.2.2 Identify Options

Based on the information gathered during the first step of this process, the design engineer compares and contrasts the options available in present day market. These feasible options, based upon the facts presented and engineering judgement of the design engineer, are then listed in the selection matrix, shown in Table 1.1.

1.2.3 Rate the Options

The options selected at the end of phase 2 are then rated based on their comparative factors such as initial cost, energy cost, maintenance, flexibility, resilience, carbon emission, etc. The rating rubric can be decided by the design engineer and the client based upon their judgement. These options, then, can be graded from best to worst and made a fact-based selection. The steps until this phase can be summarized as creating an energy model of the project, preparing estimates of cost involved in the installation and during the ownership of the system and performing life-cycle cost analysis. It is important for the design engineer to have a sound scientific narrative of each factor used during this rating as to how the numerical values were assigned to each system option, when asked upon.

Table 1.1: HVAC System Selection Matrix (Example)

HVAC System	Initial Cost	Energy Cost	Maintenance	Flexibility	Resiliency	Carbon	Total average
System #1	5.0	4.9	4.8	3.5	1.0	1.0	3.8
System #2	3.4	5.0	5.0	5.0	1.5	1.5	4
System #3	1.0	2.8	2.8	3.5	5.0	5.0	2.5

1.2.4 Evaluate Data

To ensure the existence of unanimous agreement between the design engineer and client, all participants should be present during this phase, where the design engineer along with the client reviews all the inputs, analysis and assigned grading values before publishing the final version of said matrix. Then the final selection of a high-performance HVAC system can be made which will be installed in the facility after the end of this process.

1.3 Task List and Methodology

The group selected three HVAC system that will meet all the rules and requirements that ASHRAE provides, including the following desired qualities:

- Lower Life Cycle Cost
- Lower Environmental Impact
- Comfort and Health
- Creative High-Performance Green Design

The following tasks must be accomplished before delivering the final HVAC system.

1. Run System Calculations**:** Using the TRACE software, the engineer runs various systems against the previously modeled building and previously calculated heat loads.
2. System Selection**:** With the data from the systems calculation, the engineer decides upon what system or combination of systems to use. This involves input from the ASHRAE advisors.
3. Run Energy Analysis**:** With the TRACE software, the engineer runs an energy analysis for the selected system(s).

4. Run Life Cycle Analysis: With the TRACE software, the engineer ran a life cycle analysis for the selected system(s).
5. Duct layout: For the selected system(s), the engineer will layout ductwork that will run throughout the archives center.
6. Cost of ownership analysis: The total cost of ownership is the sum of initial purchase cost and the costs of entire operation through the time of consideration. Assessing this cost means taking a bigger picture look at the value of the product over time. After the engineer finalized the three finalists systems to be used for ASHRAE project, this project summarizes the full cost of ownership analysis in all three systems, not just the energy consumption, but installation cost, longevity, cost of utilities and maintenance cost over the years and propose the ideal system depending on the type of owner, whether it is private party or a government entity, and what his plans are for this proposed building. This is called the "Total cost of ownership analysis". This step is the one that is explained in this particular report and submitted for the partial fulfillment of Honors credit.
7. Prepare Report**:** If the analyses run on the selected system(s) give values adhering to the ASHRAE standards so that the engineer will not have to go back to task 1 and select different systems, the engineer will then create a report and presentation detailing what system was selected and how they came to that decision.

The design team decided upon the final 3 systems to be analyzed, and as the Honors Senior project, this report runs an elaborate total cost of ownership analysis in those three systems, and provides the client with an informed recommendation on which one to use as per his requirements and financial optimality.

CHAPTER 2

SYSTEMS SELECTED FOR ANALYSIS

After weeks of load analysis in the building, the design team has considered three HVAC units which can meet the condition specifications of the archive facility. They are discussed in detail in this section. This was a team effort.

2.1 Single Package

The first system which considered was a single package HVAC unit. This unit is a self-contained air conditioning system which is commonly found in hotel rooms, apartments, and small houses. These self-contained units use coils and refrigerant to heat or cool outside air and transport it inside the building. To cool, the compressor pumps refrigerant to cool the coils which attracts heat and humidity which is then exhausted outside. To heat, the refrigerant is used to heat the coils and when cool air passes over the coils it turns into hot air which is pushed into the room. Out of the three considered systems, the single package unit is the cheapest to install and maintain. It also is the smallest and therefore saves space. However, it is most applicable to single-family homes and as it is not capable of storing energy.

2.2 Variable Refrigerant Flow (VRF) System

The second unit considered is Variable Refrigerant Flow (VRF) system. As the system name implies, the VRF system utilizes refrigerant to heat and/or cool a building by pumping it through a centrally located, multi-speed compressor to spread out, individual HVAC units. The multi-speed compressors allow the VRF unit to continually operate which reduces the severity of temperature spikes that can occur from a traditional HVAC unit shutting on and off. VRF units are ideal for applications with varying loads or where zoning is required due to different temperature and/or humidity requirements. VRF systems are known for their long-term economic advantages, quiet and ductless setup, and unique ability to simultaneously heat and cool different spaces within the same building. However, VRF systems cannot store energy and are expensive to install and maintain. The specific VRF unit being considered is a Heat Recovery system by LG that uses refrigerant R410A.

2.3 Water Source Heat Pump (WSHP)

The second system under consideration was Water Source Heat Pump (WSHP) unit. This unit is based on a mechanical, reversible cycle which cools or heats a building by transporting water through a series of mechanical equipment such as pipes, pumps, heat exchangers, etc. A major factor in choosing a WSHP unit is its proximity to the closest body of water as long-distance piping and pumping can drive costs up. The advantages of a WSHP unit include low installation and operating costs, reliability, design flexibility due to the availability of several WSHP system types, minimal space usage, and ease of maintenance and repair. Additionally, a WSHP unit uses less energy and provides a longer service life than a VRF system. However, WSHP units are loud which can disrupt building occupants, requires a separate ventilation system, and is limited in its filtration capability. Additionally, it does not have the ability to simultaneously heat and cool. The specific WSHP unit under consideration is produced by AAON. But WSHP being a central cooling system which has no heat rejection and having a much higher maintenance cost and capital cost, it is not further taken into consideration for the archive center. This system is much applicable as a residential HVAC system.

CHAPTER 3

TOTAL COST OF OWNERSHIP METHODOLOGY & ANLYSIS

The National Institute of Standards and Technology (NIST) has developed the Building Life Cycle Cost (BLCC) Programs, which can be installed to any laptop through Department of Energy, to provide computational support for the analysis of capital investments related to HVAC in buildings. Some systems might have higher initial costs but their lower operating costs over the projected life period might compensate the initial higher cost. This particular condition is checked through the BLCC program. It is also useful in evaluating the costs and benefits of energy and water conservation and renewable energy projects. BLCC also calculates comparative economic measures for alternative designs, including net savings, savings-to-investment ratio, adjusted internal rate of return, and years to payback. This software, and this project, is based on the "Life-Cycle Costing Manual for the Federal Energy Management Program", NIST Handbook 135 (1995).

BLCC version 5.3 has six modules, all of them consistent with the life-cycle cost methodology for Federal programs but the interface can easily be modified to include default inputs and nomenclature when specific need arises. Current utility rates in India, (electricity and natural gas), and equipment costs are obtained through government websites of India and they are projected for inflation or depreciation as per the regulations in NIST Handbook 135.

3.1 Formulae and Terminologies Used

3.1.1 Single Present Value and Uniform Present Value Factors for Non-fuel Costs

Since the value of different currencies (dollars) change with time, it is imperative to compare the prices holding their purchase power constant at present time. Few new concepts, pertaining to the concepts of accounting, are to be introduced during the analysis, as per the NIST Handbook 135.

Single Present Value: Present Value of a single amount, commonly known as SPV, is defined as current value of a future amount of money evaluated at a certain interest rate. These values are obtained from Table A-1 of NIST Handbook 135 (Annual Supplement). Then the formula that can be used for finding the present value (P), for a discount rate(d) and number of years between present time and the time of subject incurred in year t (C_t) is the following:

$$P = C_t * \frac{1}{(1+d)^t} = C_t * SPV \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Similarly, uniform present value (UPV) is used to find the present value of future costs other than fuels recurring annually, for example maintenance cost. The formula to find the present value (P) of an annually recurring uniform cost (A), with discount rate of d and number of time periods (years) N, can be given as:

$$P = A * \frac{(1+d)^N - 1}{d(1+d)^N} = A * UPV_N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

This formula can also be extended to find the present values of future energy costs or savings is the following:

$$P = A_0 * \sum_{t=1}^{N} \frac{I_{2020+t}}{(1+d)^t} = A_0 * UPV_N^* \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, A_0 = annual cost of energy as of the base date (date of implementation)

T = number of years from the base date

N = number of periods i.e. years over which the energy cost accrues

I_{2020+t} = projected average fuel price index as stated in Tables Ca-1 through Ca-5 of NIST Handbook 135

d = the real discount rate

Similarly, the UPV* factors to find the present value of annually recurring non-fuel costs which are predicted to change annually at a constant rate of change (or escalation rate) over the period of concern. This rate can either be negative or positive. For an annually recurring cost at current date price, A_0, and the rate of escalation rate e, the present value for N number of years of projection is given as:

$$P = A_0 \left(\frac{1+e}{d-e}\right)\left[1-\left(\frac{1+e}{1+d}\right)^N\right] = A * UPV_N^* \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

In this formula, the discount rate (d) cannot be equal to the escalation rate (e). The values for this equation are obtained from Tables A-3 (a, b, c) of NIST Handbook 135. It is important to note that if the discount rate is stated in terms of general inflation, then the escalation rate also must be expressed in terms of general inflation.

3.1.2 Energy Price Indices for Private Sector Analysis

Since the purchase price of dollar changes as the years go by, it is important to find out the effects of positive inflation rates to the prices of energy consumption as well. Projected fuel price index is used to analyze this effect of inflation on energy consumption computation. To find the projected fuel price index for general four alternative inflation rates of 2%, 3%, 4%, and 5% by end-use sector category and the fuel type, Tables S-1 through S-5 of the NIST Handbook 135 (Annual Supplement 2019) can be used. The values in the said tables are calculated using the following formula:

$$I_s = I_c * (1 + g)^N \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

where, I_s = are the required indices for fuel prices and put into Tables S-1 through S-5

I_c = Indices found in Table Ca-1 to Ca-5 of the Handbook

g = annual estimated rate of general price inflation

N = number of years to the projection

To select the index from the Tables provided, the column with the projected inflation rate, say 3%, is selected and the row with the year, for example 2025, is chosen for each type of energy consumption depending on the system of choice. A snapshot of Table S-1 is shown in the Appendix of this report. This given table only accounts up to 2049, but this projection was made for until 2070, equation 5 was used to calculate the projection rates for the years not provided in the Table.

These formulae are incorporated into the BLCC program and the excel sheet, and after finding the appropriate values for the variables in the right side of the equations, finding present values of those quantities can be done with convenience and the comparisons are made eventually.

3.2 Single Package System Analysis

For the single package system, also known as the baseline system, the energy cost was used at the rate of $5.81 per kWh and 4% escalation rate after that year. Moreover, for discounted rate a 3% discount rate was applied to the system which lowers the capital, energy and maintenance cost and deflation rate for the system.

These values were then input to the BLCC program which then returns the excel sheet containing the life cycle analysis, initial costs of the HVAC system and breakdown of total incurred cost.

3.3 VRF System Analysis

Similarly, for air-cooled variable refrigerant flow system, capital cost was based on per square footage and the energy cost was used at the rate of $3.63 per kWh and for discounted rate a 3% discount rate was applied to the system which lowers the capital, energy and maintenance cost and deflation rate for the system.

These values were then input to the BLCC program which then returns the excel sheet containing the life cycle analysis, initial costs of the HVAC system and breakdown of total incurred cost. A snapshot of the excel sheet is shown in Appendix A. For both of these systems, the commercial electricity prices were same. The electricity prices in India was found to be 0.078 USD for kWh, and it increases about 2-2.4% every year on average. Similarly, it was 92 cents per kiloliter for water and 3.71 USD per gallon. These data when plugged in into the TRACE 700 software determined the required energy load for each system, which was performed by the team.

Once the energy consumption was figured out, the cost analysis of HVAC system over 50 years, as specified by the competition guidelines, which was done using the discounted and inflation rate for 2019 provided by NIST handbook that were real rate of 3%, nominal rate of 3.1% and inflation rate to 0.1%. It is very important to note that economical models are not even good projecting 20 years into the future, so the idea of projecting 50 years seems farfetched. The focus was to predict the life cycle of the equipment that are being evaluated for about 15-20 years which is the actual age of the equipment used before needing replacement.

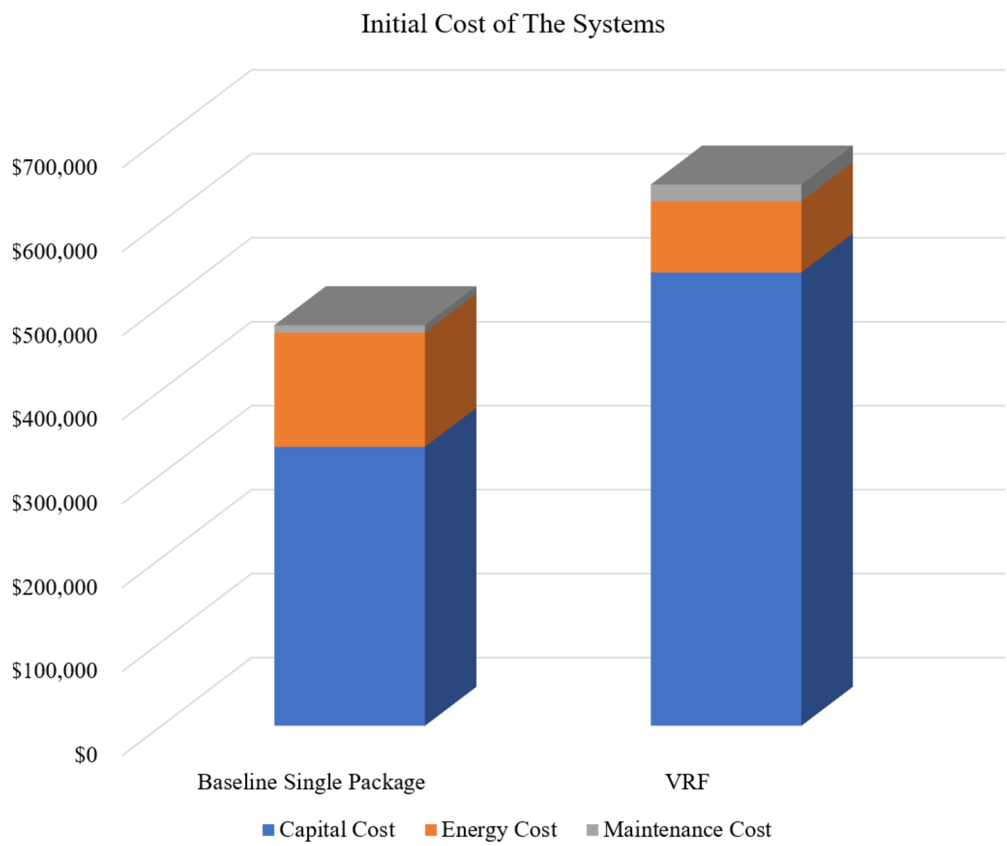

Figure 3.1: Initial Cost Comparison of Two Systems

The study of Figure 3.1 and Table 3.1 clearly suggests the initial cost of Baseline Single Package system is significantly lower, about $ 167,000, than the initial cost of VRF system. But this is not an obvious choice, as it is critical to learn about the projected cost of systems which is going to incur in the future. The excel sheet is formulated to project the cost for next 50 years, up to 2070 AD. Then the net costs of two systems for 50 years is shown in Figure 3.2.

Table 3.1: Breakdown of Initial Cost Comparison

	Baseline Single Package	VRF
Capital Cost	$332,150	$539,875
Energy Cost	$135,975	$84,875
Maintenance Cost	$9,000	$20,000
Total	$477,125	$644,750

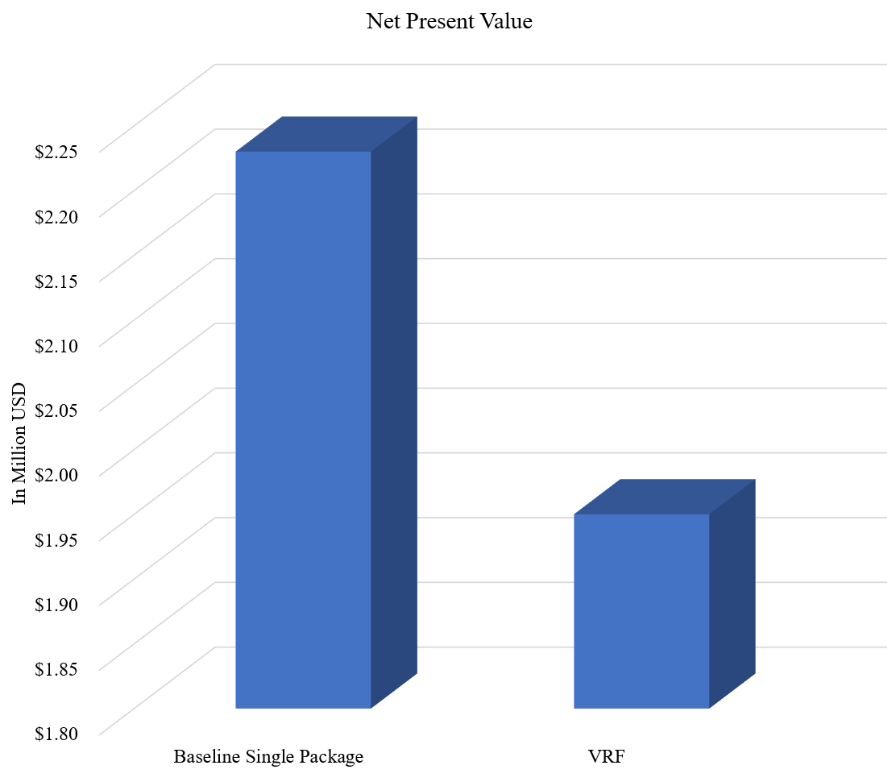

Figure 3.2: 50 Year Projection for Cost of Two Systems

Before quickly diving into the numerical comparison of the analysis, the HVAC engineer should also take note that the single package system has a higher loads per cost ratio than the VRF system. It has no heat rejection, just like in WSHP. It also is what is called a “architecture air cooled technique” which is a common design strategy which requires having a plenum between the building roof and surface which acts as a radiator. A baseline system leads to no roof spaces, generating more heat in the internal mechanical rooms. VRF system, in the other hand, has several advantages over other types of systems.

A VRF system uses refrigerant for heat rejection which is more efficient, and thus needs no water treatment. Moreover, it being a variable speed compressor has a better heat recovery mode when need be. VRF does not need a cooling tower maintenance from time to time and thus has lesser maintenance as well as energy costs.

To top it all, the evidence from the graphs, despite the baseline single package have cheaper initial cost, its cost over time increases significantly from that of VRF system. Moreover, the VRF system has other functional and operational advantages over the baseline single package system apart from the economic advantage over time as well, as explained in Chapter 2 of this report. Thus, VRF system is the most suitable to be used in the archive facility in Mumbai, India.

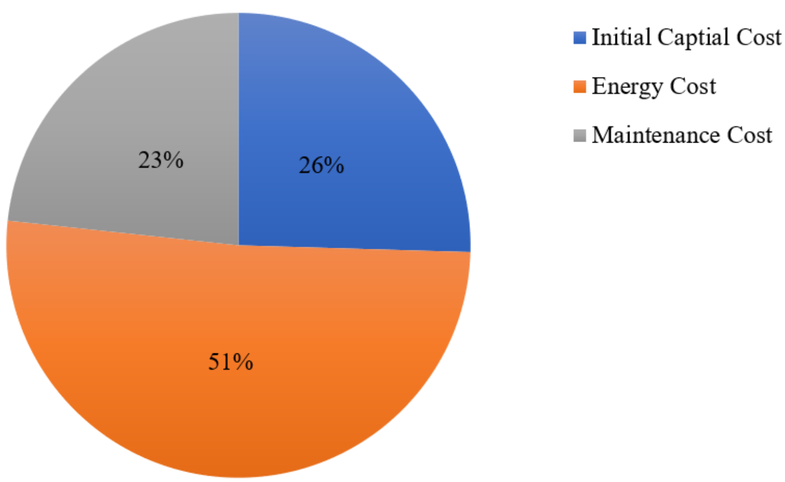

Figure 3.3: VRF System-Life Time Cost Breakdown for 50 Years

It is important to note that the analysis shows more than half of the net price projection has yielded from the Maintenance cost for the system. This amount is almost as much the owner has to pay during the installation of the system upfront. This pie chart illustration is used to show the client how much he can expect to spend on the system if he decides to own it for 50 years, as per the competition regulations. But, in reality, HVAC systems, more than often than not, need replacement in every 20 to 25 years.

CHAPTER 4

CONCLUSION

Designing a HVAC system for a given sets of conditions is a methodic approach and can be divided into steps. The design process is cumbersome in the first glance, but half the work is done when the load calculations are performed in the TRACE 700 software. After that, the process involves finding appropriate equipment which can take the conditions to required temperature, humidification, and ventilation requirements. The entire process, indeed, is about finding out the correct guidelines, government regulations and industry standards to follow to reach the desired goal. After that the economic analysis was a new experience, as similar kind of venture is not undertaken during classes. But through NIST Handbook 135 guidance and the use of their BLCC software, the process was easier and provided new insights to the economic side of engineering applications.

The findings of this project are that the VRF system, despite having greater initial cost, performs well over time economically than other systems. VRF system also has several other functional advantages over other systems, such as ease of access, lesser time spent for maintenance and better heat rejection for this comparatively smaller building of only 17,500 square feet and serving as an archive facility to old books and recordings. However, most of the expenditure would be about maintaining the system every year to make the system last longer.

APPENDIX A

SNAPSHOT OF ONE SPREADSHEET USED IN THE ANALYSIS

ASHRAE Student Design Competition
HVAC System Life Cycle Cost Comparison

Methodology: US Federal Life Cycle Cost Analysis per NIST Handbook 135 Procedure

Baseline Single Package

System Type	Cost Category	2020	2021	2022	2023	2024	2025	2026	2027	2028
Current $	Capital Cost	$332,150								
	Energy Cost	$135,975	$141,414	$141,414	$141,414	$141,414	$141,414	$141,414	$141,414	$141,414
	Maintenance Cost	$9,000	$9,000	$9,000	$9,000	$9,000	$9,000	$9,000	$9,000	$9,000
	Total Cost	$477,125	$150,414	$150,414	$150,414	$150,414	$150,414	$150,414	$150,414	$150,414
Discounted $	Capital Cost	$332,150								
	Energy Cost	$135,975	$131,803	$120,300	$110,956	$102,338	$99,463	$98,651	$92,904	$87,492
	Maintenance Cost	$9,000	$8,738	$8,483	$8,236	$7,996	$7,763	$7,537	$7,318	$7,105
	Total Cost	$477,125	$140,541	$128,783	$119,192	$110,335	$107,227	$106,188	$100,222	$94,597
	Net Present Value	**$2,230,950**								

Air-Cooled Variable Refrigerant Flow System

System Type	Cost Category	2020	2021	2022	2023	2024	2025	2026	2027	2028
Current $	Capital Cost	$539,875								
	Energy Cost	$84,875	$84,875	$84,875	$84,875	$84,875	$84,875	$84,875	$84,875	$84,875
	Maintenance Cost	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000
	Total Cost	$644,750	$104,875	$104,875	$104,875	$104,875	$104,875	$104,875	$104,875	$104,875
Discounted $	Capital Cost	$539,875								
	Energy Cost	$84,875	$79,107	$72,203	$66,595	$61,422	$59,697	$59,209	$55,760	$52,512
	Maintenance Cost	$20,000	$19,417	$18,852	$18,303	$17,770	$17,252	$16,750	$16,262	$15,788
	Total Cost	$644,750	$98,524	$91,054	$84,897	$79,192	$76,949	$75,959	$72,022	$68,300
	Net Present Value	**$1,951,577**								

System Comparison

System Type	Cost Category	2020	2021	2022	2023	2024	2025	2026	2027	2028
Current $	**Difference in Cash Flow**	($167,625)	$45,539	$45,539	$45,539	$45,539	$45,539	$45,539	$45,539	$45,539
	Simple Payback	3.7								
Discounted $	**Difference in Cash Flow**	($167,625)	$42,017	$37,729	$34,295	$31,143	$30,278	$30,229	$28,200	$26,297
	Discounted Payback	N/A, does not pay back								

APPENDIX B

SNAPSHOT OF TABLES FROM THE NIST HANDBOOK 135

Table A-3a. UPV* factors for finding the present value of annually recurring costs changing at a constant escalation rate, DOE discount rate.

DOE discount rate = 3.0%

Modified Uniform Present Value (UPV*) Factors (non-fuel)

Annual rate of price change

Number of years from base date	-5%	-4%	-3%	-2%	-1%	-0.1%	0%	1%	2%	3%	4%	5%
1	0.92	0.93	0.94	0.95	0.96	0.97	0.97	0.98	0.99	1.00	1.01	1.02
2	1.77	1.80	1.83	1.86	1.89	1.91	1.91	1.94	1.97	2.00	2.03	2.06
3	2.56	2.61	2.66	2.72	2.77	2.82	2.83	2.88	2.94	3.00	3.06	3.12
4	3.28	3.37	3.45	3.54	3.63	3.71	3.72	3.81	3.90	4.00	4.10	4.20
5	3.95	4.07	4.19	4.32	4.45	4.57	4.58	4.72	4.86	5.00	5.15	5.30
6	4.56	4.72	4.89	5.06	5.24	5.40	5.42	5.61	5.80	6.00	6.21	6.42
7	5.13	5.33	5.55	5.77	5.99	6.21	6.23	6.48	6.73	7.00	7.28	7.57
8	5.66	5.90	6.16	6.44	6.72	6.99	7.02	7.33	7.66	8.00	8.36	8.73
9	6.14	6.44	6.75	7.08	7.42	7.75	7.79	8.17	8.57	9.00	9.45	9.92
10	6.58	6.93	7.30	7.68	8.09	8.49	8.53	8.99	9.48	10.00	10.55	11.13
11	7.00	7.39	7.81	8.26	8.74	9.20	9.25	9.80	10.38	11.00	11.66	12.37
12	7.37	7.82	8.30	8.81	9.36	9.89	9.95	10.59	11.27	12.00	12.78	13.63
13	7.72	8.22	8.76	9.34	9.96	10.57	10.63	11.36	12.15	13.00	13.92	14.91
14	8.05	8.59	9.19	9.83	10.54	11.22	11.30	12.12	13.02	14.00	15.06	16.22
15	8.34	8.94	9.60	10.31	11.09	11.85	11.94	12.87	13.89	15.00	16.22	17.56
16	8.62	9.27	9.98	10.76	11.62	12.46	12.56	13.60	14.74	16.00	17.39	18.92
17	8.87	9.57	10.34	11.19	12.13	13.06	13.17	14.32	15.59	17.00	18.57	20.30
18	9.10	9.85	10.68	11.60	12.62	13.63	13.75	15.02	16.43	18.00	19.76	21.72
19	9.32	10.11	11.00	11.99	13.09	14.19	14.32	15.71	17.26	19.00	20.96	23.16
20	9.52	10.36	11.30	12.36	13.54	14.74	14.88	16.38	18.08	20.00	22.17	24.63
21	9.70	10.59	11.58	12.71	13.98	15.26	15.42	17.05	18.90	21.00	23.39	26.12
22	9.87	10.80	11.85	13.04	14.40	15.77	15.94	17.69	19.70	22.00	24.63	27.65
23	10.03	11.00	12.10	13.36	14.80	16.27	16.44	18.33	20.50	23.00	25.88	29.21
24	10.17	11.18	12.34	13.66	15.18	16.75	16.94	18.96	21.29	24.00	27.14	30.79
25	10.30	11.35	12.56	13.95	15.56	17.21	17.41	19.57	22.08	25.00	28.41	32.41
26	10.42	11.51	12.77	14.23	15.91	17.67	17.88	20.17	22.85	26.00	29.70	34.06
27	10.54	11.66	12.97	14.49	16.26	18.10	18.33	20.76	23.62	27.00	31.00	35.74
28	10.64	11.80	13.16	14.73	16.59	18.53	18.76	21.34	24.38	28.00	32.31	37.45
29	10.74	11.93	13.33	14.97	16.90	18.94	19.19	21.90	25.14	29.00	33.63	39.20
30	10.82	12.05	13.50	15.20	17.21	19.34	19.60	22.46	25.88	30.00	34.97	40.98

Table A-1. SPV factors for finding the present value of future single costs (non-fuel)

	Single Present Value (SPV) Factors		
	DOE Discount Rate	OMB Discount Rates[a] Short Term[b]	Long Term[c]
Number of years from base date	3.0%	1.3%	1.5%
0.25	0.993	0.997	0.996
0.50	0.985	0.994	0.993
0.75	0.978	0.990	0.989
1	0.971	0.987	0.985
2	0.943	0.974	0.971
3	0.915	0.962	0.956
4	0.888	0.950	0.942
5	0.863	0.937	0.928
6	0.837	0.925	0.915
7	0.813	0.914	0.901
8	0.789	0.902	0.888
9	0.766	0.890	0.875
10	0.744	0.879	0.862
11	0.722		0.849
12	0.701		0.836
13	0.681		0.824
14	0.661		0.812
15	0.642		0.800

Table Ca-1. Projected fuel price indices (excluding general inflation), by end-use sector and fuel type.

Census Region 1

Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont

Projected April 1 Fuel Price Indices (April 1, 2019 = 1.00)

Sector and Fuel	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Residential															
Electricity	1.01	1.02	1.03	1.04	1.07	1.09	1.11	1.12	1.13	1.13	1.14	1.14	1.15	1.16	1.16
Distillate Oil	1.02	1.04	1.06	1.08	1.13	1.16	1.18	1.20	1.22	1.24	1.25	1.26	1.27	1.29	1.29
LPG	1.08	1.14	1.19	1.23	1.28	1.32	1.36	1.39	1.42	1.43	1.45	1.45	1.46	1.48	1.49
Natural Gas	1.02	1.04	1.07	1.11	1.15	1.17	1.18	1.19	1.19	1.20	1.20	1.21	1.21	1.22	1.23
Commercial															
Electricity	0.99	0.99	0.99	1.00	1.02	1.04	1.06	1.07	1.09	1.09	1.09	1.10	1.11	1.12	1.13
Distillate Oil	1.00	0.97	0.94	0.92	0.92	0.94	0.96	0.99	1.00	1.02	1.03	1.04	1.05	1.06	1.07
Residual Oil	1.02	1.11	1.18	1.28	1.41	1.47	1.51	1.58	1.61	1.66	1.68	1.70	1.73	1.75	1.77
Natural Gas	1.01	1.03	1.07	1.11	1.16	1.18	1.19	1.19	1.20	1.20	1.20	1.20	1.20	1.21	1.22
Coal	1.00	1.00	1.00	1.00	1.01	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03

Table S-1. Projected fuel price indices with assumed general price inflation rates of 2%, 3%, 4%, and 5%, by end-use sector and fuel type.

Census Region 1

Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont

Projected April 1 Fuel Price Indices (April 1, 2019 = 1.00)

Residential

Year	Electricity Inflation Rate				Distillate Oil Inflation Rate				LPG Inflation Rate				Natural Gas Inflation Rate			
	2%	3%	4%	5%	2%	3%	4%	5%	2%	3%	4%	5%	2%	3%	4%	5%
2020	1.03	1.04	1.05	1.06	1.05	1.06	1.07	1.08	1.10	1.11	1.12	1.13	1.04	1.05	1.06	1.07
2021	1.07	1.09	1.11	1.13	1.09	1.11	1.13	1.15	1.18	1.21	1.23	1.25	1.09	1.11	1.13	1.15
2022	1.10	1.13	1.16	1.20	1.12	1.16	1.19	1.22	1.26	1.30	1.34	1.38	1.14	1.17	1.21	1.24
2023	1.13	1.18	1.22	1.27	1.17	1.22	1.27	1.32	1.34	1.39	1.44	1.50	1.20	1.25	1.30	1.35
2024	1.18	1.24	1.30	1.36	1.24	1.30	1.37	1.44	1.41	1.48	1.55	1.63	1.27	1.33	1.40	1.47
2025	1.23	1.30	1.38	1.46	1.30	1.38	1.46	1.55	1.49	1.57	1.67	1.77	1.32	1.40	1.48	1.57
2026	1.27	1.36	1.46	1.56	1.35	1.45	1.55	1.66	1.56	1.67	1.79	1.91	1.36	1.45	1.56	1.66
2027	1.31	1.41	1.53	1.65	1.41	1.53	1.65	1.78	1.63	1.76	1.90	2.05	1.39	1.51	1.63	1.76
2028	1.35	1.48	1.61	1.76	1.46	1.59	1.73	1.89	1.69	1.85	2.02	2.20	1.43	1.56	1.70	1.85
2029	1.38	1.52	1.68	1.85	1.51	1.66	1.83	2.01	1.75	1.93	2.12	2.34	1.46	1.61	1.77	1.95
2030	1.42	1.58	1.75	1.95	1.55	1.73	1.92	2.14	1.80	2.00	2.23	2.47	1.49	1.66	1.85	2.06
2031	1.45	1.63	1.83	2.05	1.60	1.79	2.01	2.26	1.85	2.07	2.33	2.61	1.53	1.72	1.93	2.17
2032	1.49	1.69	1.92	2.17	1.64	1.87	2.12	2.40	1.89	2.15	2.44	2.76	1.57	1.78	2.02	2.29
2033	1.53	1.75	2.01	2.29	1.70	1.94	2.23	2.54	1.95	2.23	2.56	2.92	1.61	1.85	2.12	2.42
2034	1.57	1.81	2.10	2.42	1.74	2.01	2.33	2.69	2.01	2.32	2.68	3.10	1.65	1.91	2.21	2.55
2035	1.60	1.88	2.19	2.55	1.79	2.09	2.44	2.84	2.06	2.41	2.81	3.28	1.69	1.98	2.31	2.69
2036	1.64	1.94	2.28	2.69	1.84	2.17	2.56	3.01	2.12	2.50	2.95	3.47	1.73	2.05	2.41	2.84
2037	1.68	2.00	2.39	2.83	1.88	2.24	2.67	3.17	2.18	2.60	3.09	3.67	1.78	2.12	2.52	3.00
2038	1.72	2.07	2.48	2.98	1.92	2.32	2.78	3.34	2.24	2.69	3.23	3.88	1.82	2.19	2.63	3.16
2039	1.75	2.12	2.58	3.12	1.97	2.40	2.91	3.52	2.29	2.79	3.38	4.09	1.86	2.26	2.74	3.32
2040	1.77	2.17	2.66	3.25	2.02	2.48	3.04	3.72	2.35	2.88	3.53	4.32	1.91	2.34	2.87	3.50

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BIOGRAPHICAL INFORMATION

Pawan Panth is an undergraduate senior in mechanical engineering at the University of Texas at Arlington, set to graduate in May 2020 with Honors. Pawan's future goal is to earn a Ph.D. in dynamic system and controls to pursue his love for the field and dive in deeper to the realms of mathematics and system dynamics. Pawan also undertook the optimal control for dynamic systems and analytical-computational dynamic graduate classes in his final semester of his undergraduate degree to prepare himself for the Ph.D. program he is applying to. Pawan has worked with Dr. Adnan Ashfaq in his research lab in the Summer of 2017 as part of Honors College Undergraduate Research Fellowship program. Pawan has worked as a Mechanical Engineering intern in Viking Range LLC, a luxury consumer goods manufacturing company in Greenwood, Mississippi, for a year. During his time in the internship he built a good rapport with his supervising officer and was able to get job invitation after he graduates. But Pawan wants to continue his academic career further before joining the workforce permanently. During his undergraduate career, Pawan has won several awards as scholarships and has been in the Dean's list of College of Engineering for five straight semesters.