Application of an Efficient Heat Recovery System for Sustainable Development

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1 Introduction

Technology advancement has led to an increase in the need for energy in the modern world. Saving energy will reduce expenditures for consumers, industries, and associated health issues. Optimization plays a crucial part in enhancing sustainability overall by optimizing resources, such as the triple bottom line, by achieving the goals of the three P's, which are environmental, social, and economic sustainability, as well as by focusing on the sustainability of energy resources by satisfying the objective functions.

One of the leading causes of energy waste is the heating system of a manufacturing facility. An efficient heating system should be used in industrial settings to offer a comfortable working atmosphere for both the workers in the offices and the production areas. Our project provides an ideal, real-life energy-efficient design for a manufacturing facility with the installation of a Heat Recovery System (HRS), which warms the water for the central heating system using the hot oil consumed by the compressors, optimizing the investment cost as well. The heating system makes the working environment more comfortable in terms of temperature, while the cooling system lowers the oil temperature in the air compressors or hydraulic systems to enable continued operation. The compressor of heating system is considered as a major source of energy consumption which also increases the cost. The objective of our project is to minimise energy consumption, the cost, and maximizing savings related to heating system. To achieve this goal, we used mixed integer linear programming (MILP) optimization model by considering the circular economy, sustainability, and energy efficiency.

In our project, we optimized the extra energy consumption cost, the cost which are not directly assigned to HRS, fixed investment cost, marginal cost of additional compressor and savings. Apart from our source paper [1], we also implemented a new objective function and three constraints that minimises energy consumption to make our project sustainable.Finally we analysed our result of cost and energy consumption by varying number of areas and compressor of our heat recovery system.

2 Related Work

Energy efficiency is regarded as an essential component for maintaining sustainability. In order to tackle the energy efficiency paradox, industrial waste heat recovery devices are a hot issue in research circles. Waste recovery system is explained by incorporating heat exchanger networks and thermal engines with utilities, refrigeration, and electricity production. This work proposed an efficient method for recovering industrial waste heat. Here A multi-objective mixed-integer nonlinear programming (MINLP) model was developed to address an integration challenge that considers sustainability's economic, environmental, and social components [2]

Jang et al. (2013) represented an optimization technique for a thermoelectric generator. In this paper, the numerical optimization of TEG module spacing and spreader thickness employed in a waste heat recovery system is examined and solved using the finite difference approach and a simplified conjugate gradient method. Sustainable energy management has been mandatory in recent days [3]. Liu et al. present a multi-objective optimization (MOO) framework for the extended integration of interplant heat exchanger networks (HENs) and the shared utility system, taking into account the twin objectives of the economy and the environment. Here, the utility steam supply is offset in terms of interplant cooperative energy usage by permitting process streams to produce steam and utilizing the steam as an intermediary fluid for cross-plant heat recovery [4].

Lira-Barragán et al. represented a novel method for synthesizing sustainable trigeneration systems (heating, cooling, and power generation cycles) connected with heat exchanger networks. To generate electricity and heat processes, the steam Rankine cycle can be powered by various primary energy sources, including solar, biofuels, and fuels. In order to create electricity and process cooling below the ambient temperature, the organic Rankine cycle and the absorption refrigeration cycle can be driven by the steam Rankine cycle's waste energy and/or surplus process heat. The synthesis problem is written as a multi-objective mixed-integer nonlinear programming problem considering economic, environmental, and social dimensions of sustainability [5].

Some industries are using heat recovery systems in their production. Sigma Thermal company optimizes heating systems for cost-effective operation and provides a closed loop system that is an efficient way of capturing wasted energy and transferring it to various users, and a combustion air pre-heat system which increases overall system efficiency and minimizes system operating costs. Energy audits and/or technical advice to determine whether energy that can be recovered is wasted to reduce further operating costs [6]. Turkish subsidiary company EXERGY provides a waste heat recovery system that extracts thermal energy from industrial plant exhaust gas via oil, pressurized water, or steam as the intermediate fluid in the ORC module and transfers the heat to the organic liquid in the ORC evaporator, where the organic liquid evaporates into the turbine. This causes the steam to expand and spin the turbine and generate electricity in the generator. The vaporized organic liquid then passes through the cycle to the condenser, where it liquefies again. It passes through the pump before starting the cycle again [7].

Bosch Thermotechnology Commercial and Industrial complete solutions for heating, decentralized energy supply, air conditioning and ventilation. Their energy recovery ventilation units are operated to supply preconditioned fresh air with exhaust air through a heat exchanger, which minimizes energy loss [8]. Global Finishing Solutions deployed a heat recovery system that supplies 40-50 percent energy savings for air make-up systems suiting heating and cooling. A flat plate air-to-air heat exchanger catches heat from the exhaust air and uses that heat to heat fresh air in the booth or oven [9].

However, there is no clear indication that these organizations formulate and handle the problem as a multi-objective optimization problem. Our project differs from those regions by considering two conflicting cost-based objective functions. This design of inverse objective functions with technical issues employs goal programming. The obtained results indicate that the developed mathematical programming model is a successful decision support system because its single and multi-objective versions can identify energy-efficient production designs, real-life issues, and circular economy context.

3 System Model and Extended Problem Formulation

3.1 Formal problem Description

The project demonstrates the system that consumes the least amount of energy while minimizing the expense of heating systems. Oil is heated by the compressors at the production plant as they utilize it to create air. Another technique can be employed to bring the warmed oil's temperature down so that it may be reused while producing continuous air. As long as the machines require air for operation, compressors and temperature-lowering devices are cycled into operation. During operation, here the system that heats water for the central heating system using high-temperature oil might be installed instead of system that lowers the temperature. Figure 1 illustrates such a design which minimizes the cost of compressor cooling and the cost of central heating [1].

In the given figure 1, the pipeline has started and ended in the same Heat Recovery System (HRS). Additionally, in the central heating system, there can only be one successor and predecessor for the HRS. Moreover, in every case, the order of the compressors is determined by how much energy is used

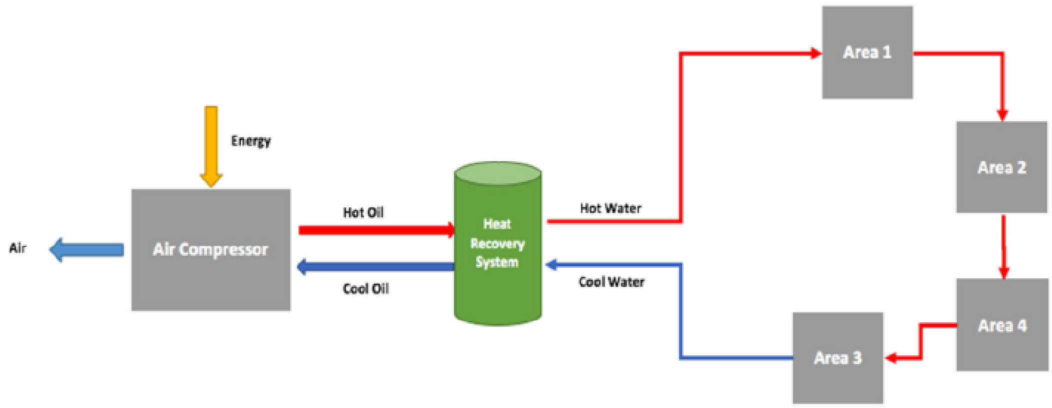

Figure 1: Design of the hot oil-powered compressor central heating system.

for cooling. It is assigned to the larger compressor first having the smaller compressor at the last. Finally, if the thermal recovery system is employed for energy efficiency, at most one compressor and one area are allocated to the system in order to identify the optimum return on investment. The design issue will be formulated as a multi-objective mixed-integer linear programming model in this section.

The model's assumptions and notations are listed in the following table:

Notation	Definition
Indices	
N	Number of areas
J	Number of compressors
M	Number of planning periods in months
i, k	Set of areas $i, k \in \{0, \cdots, N\}; 0\ is\ the\ HRS$
j	Set of compressors $j \in \{1, \cdots, J\}$
m	Set of planning periods $m \in \{1, \cdots, M\}$
Parameters	
HC_m	Unit heating cost in the month $m \in \{1, \cdots, M\}$
CC_m	Unit cooling cost in the month $m \in \{1, \cdots, M\}$
D_{jm}	Avg energy consumption to cool compressor $j \in \{1, \cdots, J\} in\ month\ m \in \{1, \cdots, M\}$
E_{im}	Avg energy consumption to heat area $i \in \{0, \cdots, N\} in\ month\ m \in \{1, \cdots, M\}$
L_{ikm}	Avg Energy Loss $i \in \{0, \cdots, N\} to\ area\ k \in \{0, \cdots, N\} inm \in \{1, \cdots, M\}$
S_j	Marginal cost of one extra compressor to the HRS
F_i	Fixed investment cost for heating system installation of area $i \in \{0, \cdots, N\}$
P_{ki}	Fixed investment cost for piping system $k \in \{0, \cdots, N\} to\ area\ i \in \{0, \cdots, N\}$
Decision Variables	
$x_i \in \{0, 1\}$	Equals 1 if the area $i \in \{0, \cdots, N\}\ is\ heated\ by\ the\ HRS,\ and\ 0\ otherwise$
$y_j \in \{0, 1\}$	Equals 1 if the compressor $j \in \{0, \cdots, J\}\ is\ assigned\ to\ the\ HRS,\ and\ 0\ otherwise$
$z_{ki} \in \{0, 1\}$	Equals 1 $i \in \{0, \cdots, N\} follows\ the\ area\ k \in \{0, \cdots, N\} in\ central\ heating\ system, 0\ otherwise$
State Variables	
$A_m >= 0$	Extra energy consumption to heat up of the areas by HRS, m $\in \{1, \cdots, M\}$
$B_m >= 0$	Extra energy consumption to cool down of the compressors, m $\in \{1, \cdots, M\}$

Table 1: Model notations and their definitions.

Here we solved the optimization problem using multi-objective mixed-integer linear programming (MILP) model. There are some assumptions that we were considered for our MILP model:

- The pipeline of the HRS is circular that means it is started and finished in the same HRS.
- Both the HRS and areas must have only one successor and predecessor in the central heating system.
- Compressor number is always ranked by descending order according to the energy consumption for the cooling.
- At least one compressor and one area are assigned to the system.
- Average energy consumption to heat up all the areas should be at most 20000 kW.
- Average energy consumption to cool down all the compressors should be at most 20000 kW.
- Average energy loss from one area to another of HRS should be at most 1500 kW.

3.2 Objective Function

The first objective function is minimising the cost of HRS. As the unit heating and cooling cost is associated with the heat recovery system, this unit cost must be multiplied by extra energy consumption to heat up the area and to cool down the compressor. Finally, this heating and cooling cost are added to get the total heating and cooling cost. By Eq. (1), the first objective function optimizes the heating cost of area and cooling cost of the compressor [1].

$$z_1 = \sum_{m=1}^{M} CC_m * B_m + \sum_{m=1}^{M} HC_m * A_m \tag{1}$$

Again, the areas and compressors that are not assigned to the HRS have some heating and cooling costs. The second part of the objective function that is represented by Eq. (2) that aims to minimize these additional areas and compressor costs. As we consider here the cost that are not assigned to HRS, we deducted heated area and cooled compressor from the total area and compressor. Here, we considered average energy consumption to cool down the compressor and heat up the areas with unit cooling and heating cost [1].

$$z_2 = \sum_{m=1}^{M} \sum_{j=1}^{J} CC_m * D_{jm} * (1 - y_j) + \sum_{m=1}^{M} \sum_{i=1}^{N} HC_m * E_{im} * (1 - x_i) \tag{2}$$

The 3rd part of the objective function minimizes the total fixed cost for installation of the HRS such as piping cost. Eq. (3) represents fixed investment cost [1].

$$z_3 = \sum_{i=1}^{N} x_i * F_i + \sum_{k=1}^{N} \sum_{i=1}^{N} Z_{ki} * P_{ki} \tag{3}$$

There might be some additional marginal cost for adding extra compressor [1].The Eq. (4) represents the total investment cost of the system.

$$z_4 = \sum_{j=1}^{J} y_j * s_j \tag{4}$$

Finally, all the cost components are summed up to create the objective function which minimises the total cost related to heat recovery system [1].

$$\min OBJ_1 = z_1 + z_2 + z_3 + z_4 \tag{5}$$

Apart from cost, we also considered savings. The total saving can be achieved if it is equal to the total cost generated from monthly energy consumption for heating and cooling [1]. In this case, all the compressors and areas are assigned to the HRS, and therefore the maximum achievable total savings can be found through Eq. (6).

$$z_5 = \sum_{m=1}^{M} \sum_{j=1}^{J} CC_m * D_{jm} * (y_j) + \sum_{m=1}^{M} \sum_{i=1}^{N} HC_m * E_{im} * (x_i) \tag{6}$$

To optimize the savings it must be maximized. The maximum saving is only possible if and only if each of the cost values determined by $z_1$and z_2 is equal to zero while creating an objective function to optimise the saving [1]. So, the saving-based objective function can be represented as:

$$\max OBJ_2 = z_5 - z_1 - z_2 \tag{7}$$

Then we implemented a new objective function that minimizes the energy consumption of our system. The average energy consumption of heating the area and cooling of the compressor is added and then deducted the average energy loss of the hot water from one area to another.

$$\sum_{j=0}^{J} D_{jm} * y_j + \sum_{i=0}^{N} E_{im} * x_i - \sum_{i=1}^{N}\sum_{k=1}^{N} L_{kim} * z_{ki} \tag{8}$$

3.3 Constraints

3.3.1 Assignment Constraints

According to our 4^{th} assumption, at least 1 compressor and 1 area must be allocated to HRS. Eq.(9) and (10) represents the assumption. Area 0 indicates the HRS centre. Eq. (11) ensures the placement of HRS centres in central heating systems [1].

$$\sum_{i=1}^{N} x_i >= 1 \tag{9}$$

$$\sum_{j=1}^{J} y_j >= 1 \tag{10}$$

$$x_0 = 1 \tag{11}$$

Eq. (12) ensures the assignment of the compressors according to their ordered sequence are considered as per the 3^{rd} assumption.

$$y_{j-1} - y_j >= 0;\ \forall j \in \{2, \ldots, J\} \tag{12}$$

3.3.2 Routing constraints

After the assignment of the area and compressor in HRS, our next task is to design the pipeline and fix the route of the flow of hot water through central heating system. This part of the model follows the travelling salesman problem (TSP) to choose the best route. According to the second assumption of the model, both the HRS and the areas allocated to the HRS must have only one successor and predecessor in the central heating system [1], which is confirmed through Eq. (13-16). Additionally, Eq. (17) represents that there must be unidirectional pipelines between the areas and HRS belonging to the central heating system.

$$\sum_{i=0}^{N} z_{ki} <= 1 \quad \forall k \in \{0, \ldots, N\} | k \neq i \tag{13}$$

$$\sum_{k=0}^{N} z_{ki} <= 1 \quad \forall i \in \{0, \ldots, N\} | i \neq k \tag{14}$$

$$x_i - \sum_{k=0}^{N} z_{ki} = 0 \quad \forall i \in \{0, \ldots, N\} | i \neq k \tag{15}$$

$$x_k - \sum_{i=0}^{N} z_{ki} = 0 \quad \forall k \in \{0, \ldots, N\} | k \neq i \tag{16}$$

$$z_{ki} \ + \ z_{ik} <= 1 \quad \forall k, i \in \{0, \ldots, N\} | k \neq i \tag{17}$$

3.3.3 Energy consumption constraints

For minimizing the energy consumption, we created 3 new constraints that limits the use of consumed energy for heating and cooling. Assumptions 5,6 and 7, which we made are implemented by these constraints.

$$\sum_{j=0}^{J} D_{jm} * y_j <= 20000 \tag{18}$$

$$\sum_{i=0}^{N} E_{im} * x_i <= 20000 \tag{19}$$

$$\sum_{i=1}^{N} \sum_{k=1}^{N} L_{kim} * z_{ki} <= 1500 \tag{20}$$

3.4 Limitations

As this is a multiobjective model, this project could be more efficient if we used any mathematical programming model and heuristic algorithm. Moreover, we assumed some random data in our project, this could be better if we could manage real life data.

4 Approaches and Methods

The mixed integer linear programming (MILP) formulation was utilized to solve the optimization problem for the heat recovery system, which we solved using the Gurobi optimization solver. Travelling salesman problem (TSP) algorithm is used in fixing the routing constraints of the heat recovery system so that hot water can move towards the optimal route.

5 Results Presentation and Analysis

To optimize the system in our project, we deployed four different types of costs. At first, we analyzed our optimized cost that is composed of extra heating and cooling cost, compressor costs that are not directly related to HRS, investment costs, and the marginal cost of extra compressor. By plotting the total cost vs variable compressor, we found that the total optimized costs are increasing with the increment of number of compressors. Because when the number of compressors are added, some additional costs are also generated such as installation cost.

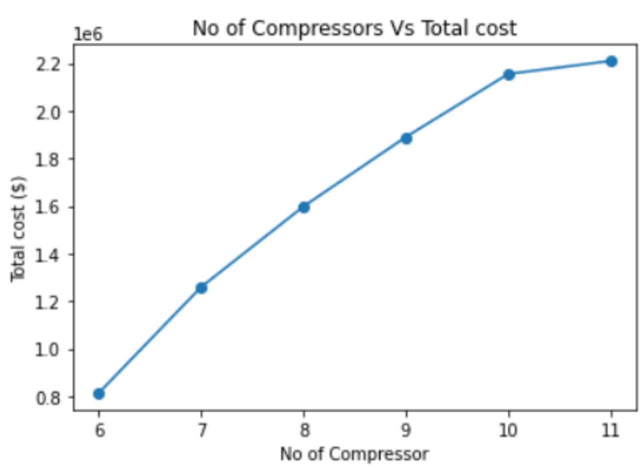

Figure 2: Number of Compressor vs Total Cost.

Next, the savings of the system are plotted by varying the number of compressors. When we increase the number of compressors, the optimized cost of the HRS is increasing. We have found the total savings by deducting extra cost of heating the area and cooling the compressor from the total cost originated from the monthly energy consumption. So, savings will be decreased as we increase the number of compressor. From the figure 3, we can analyze that the savings are decreasing at a significant rate with the increase of number of compressors.

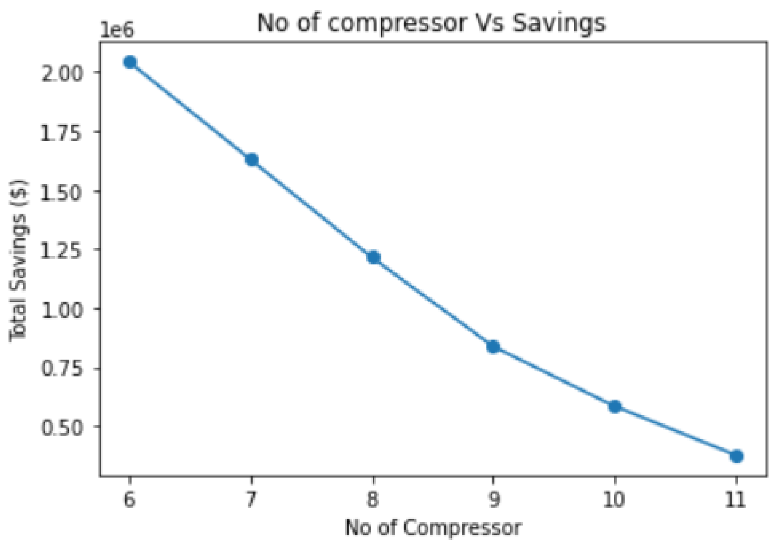

Figure 3: Number of Compressor vs Total Savings.

Furthermore, we analyzed the optimized total cost and total savings in our project by increasing the number of compressors. As the savings of our project is inversely proportional to the total cost, we found that with the number of compressor, the cost is increasing while the savings decreased. We have seen a trade off relation in between cost and savings in Figure 4..

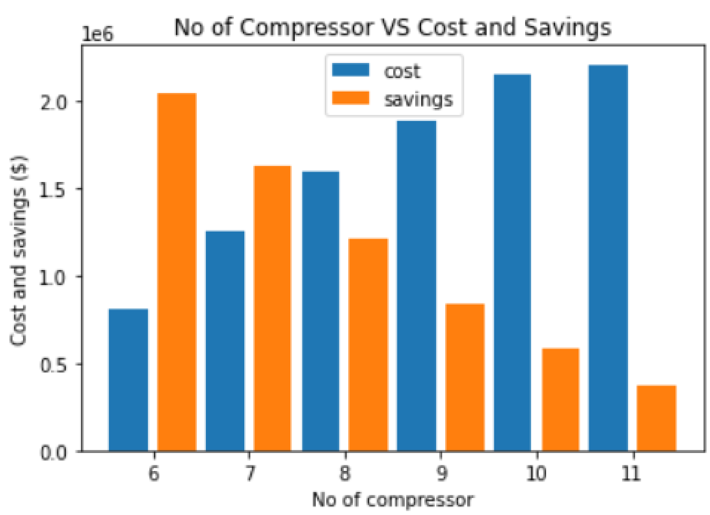

Figure 4: Number of Compressor vs Total Savings and Total Cost

Then, the total investment cost which is composed of installation cost and marginal cost of extra compressor. As this fixed investment cost is not dependent on the parameters we found that the optimized values remain constant.

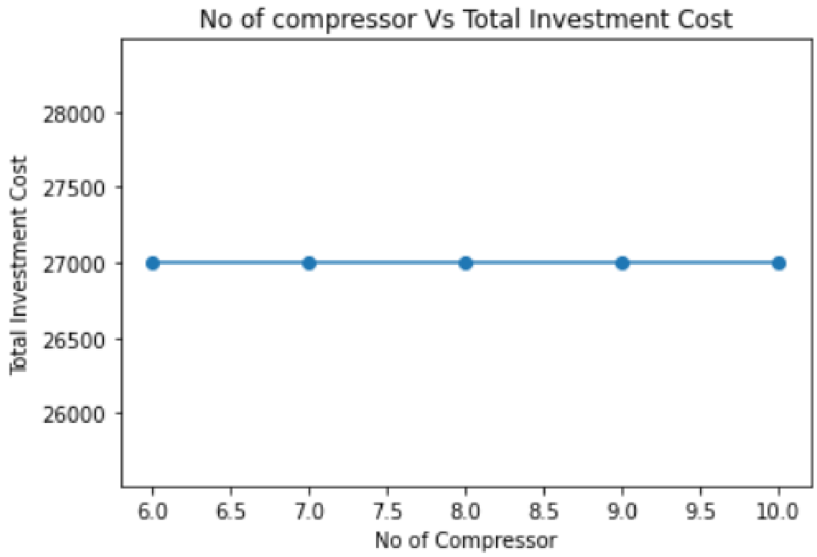

Figure 5: Number of Compressor vs Total Investment Cost

Next, the additional cost of heating and cooling was plotted while the number of compressors was varied. We can evaluate from the graph, the extra heating and cooling cost changing when we increase the number of compressors.

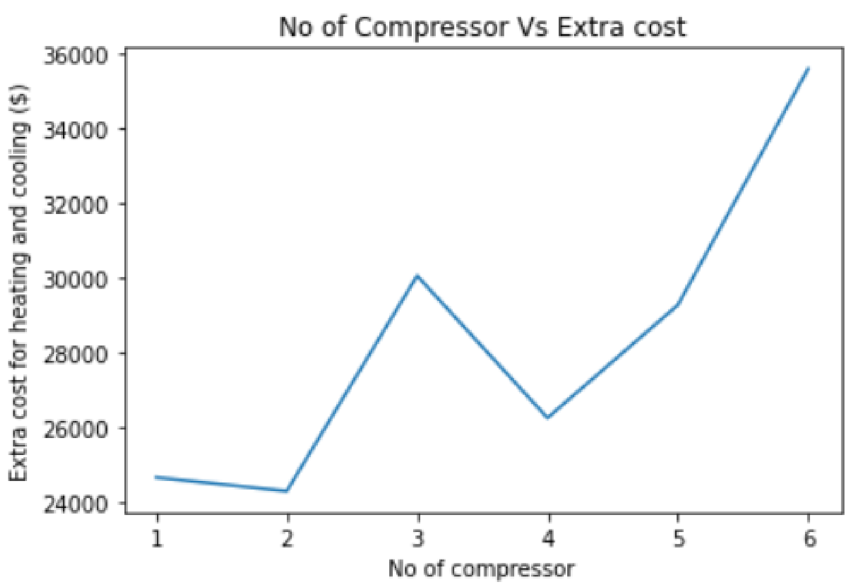

Figure 6: Number of Compressor vs Extra cost of heating and cooling

Then, in Figure 7, optimized energy consumption is plotted against different number of compressor where the energy consumption is rising sharply at a certain point. However, it begins to decline once there are more than 8 compressors.

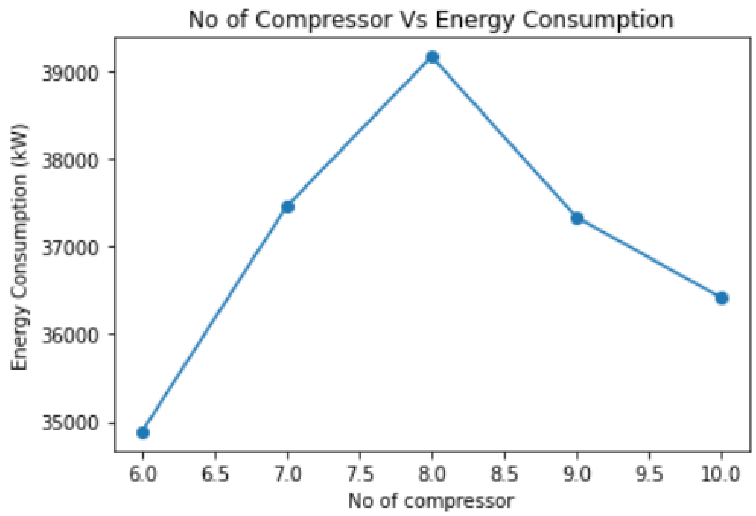

Figure 7: Number of Compressor vs Energy Consumption

Finally, energy consumption is displayed against the total cost. We observed that the graph is skewed since the energy consumption does not vary much even if the cost rises with the number of compressors increases.

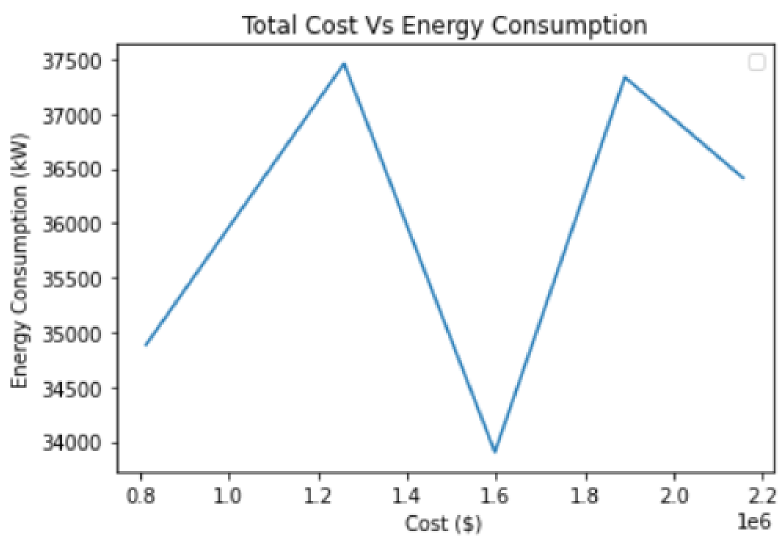

Figure 8: Cost vs Energy Consumption

6 Conclusion

Heat recovery system has been responsible for energy consumption and cost in todays world. Keeping in mind of the sustainability, we have implemented a heat recovery system that minimizes the costs and energy consumption while maximizing savings. MILP optimization formulation is used to solve the issue. We identified a trade-offs in between cost and savings. So if the cost can be minimized, the savings of the system will be maximized. In future, this project can be developed with heuristic algorithm that will positively impact the optimization result.

7 Summary

In our source paper [1] of heat recovery system, several costs and savings are optimized using single and multiobjective approach. We deployed some of their mathematical approaches into coding using Gurobi solver in python. Besides their cost and savings formulation, we generated a new objective function and three constraints that are for minimizing the energy consumption. Moreover, the result presentation and analysis section is also our own work. We have analyzed several approaches for representing the effect of optimization by varying parameters. At first, we evaluated the trend of cost and savings with increasing compressors. After that, a trade-off is presented in between the optimized cost and savings. We also plotted the investment cost and extra cost of area and compressor for heating and cooling. Finally, optimized energy consumption is plotted against compressors and cost with a thorough analysis. The challenges we faced when working on this project that there was not any other similar paper related to heat recovery system. The full implementation part of the project was developed on our own with the knowledge of Python and Gurobi. We put a lot of effort into learning Gurobi's optimization techniques, we have not re-used any portion of code and also did not find any coding related to our project.

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Part of Project	Group Member	Contribution
System Model and Extended Problem Formulation	Arpita, Abhi, Kumkum	High, High, High
Approaches and Methods	Arpita, Abhi, Kumkum	High, High, High
Results Presentation and Analysis	Arpita, Abhi, Kumkum	High, High, High
Writing and Presentation Quality	Arpita, Abhi, Kumkum	High, High, High
Formatting and References	Arpita, Abhi, Kumkum	High, High, High