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An application of a circular economy approach to design an energy-efficient heat recovery system

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ABSTRACT

This paper aims to develop an optimal real-life energy-efficient design for a production plant within the concept of the circular economy. The problem is to install a Heat Recovery System (HRS) that utilizes the hot oil used by the compressors to heat the water for the central heating system. To achieve the desired level of energy efficiency this design problem must be formulated from both the optimization and sustainability points of view. Additionally, this design problem must also consider the investment cost. In line with this purpose, this paper formulates this design problem as an optimization problem employing a mathematical programming approach as a single objective, and as a multi-objective optimization problem through a goal programming approach. Besides, this paper uses the return on investment as a key performance indicator, since it deals with a real-life design problem with an investment cost. The related design problem is solved with the single objective and multi-objective versions of the developed mathematical programming model via a commercial solver to identify different design alternatives and hence giving the decision-maker to make a selection option. Finally, the capability of the developed mathematical programming model is tested on a set of randomly generated problems. The obtained results indicate that the developed mathematical programming model is a successful decision support system since its single and multi-objective versions are capable of identifying energy-efficient production designs within the context of the real-life problem on hand and the circular economy.

1. Introduction

The energy requirement and consumption of the modern world has soared especially due to the developing technologies and therefore energy is a vital issue for modern life. Such that, energy has been the reason even for some of the wars on the earth (San-Akca et al., 2020) and domineering the energy sources is one of the most important problems of the modern world even today. On the other hand, the energy sources are not abundant and increasing energy consumption may deplete the energy sources soon. Additionally, many major climate problems are due to the unplanned usage of energy sources and this situation is already threatening life on earth. For that reason, humankind realized the vital importance of the energy sources' usage as effectively as possible, besides the usage of alternative and renewable energy sources.

In today's world, industry, households, transport, services and agriculture are the main energy consumers and due to their energy usage global warming has become probably the most important problem for all the planet earth. For that reason, the Paris Agreement has been signed to limit the temperature increase to 1.5 °C to limit the global temperature increase to less than 2 °C (Román and Galarraga, 2016). Meanwhile, energy efficiency has arisen as a measure proposed to reduce energy consumption (del Mar Solà et al., 2021) and therefore the greenhouse gas and CO_2 emissions. Energy efficiency may also reduce costs for industries and individuals, decrease local pollutants and related health problems. However, the energy efficiency investments are not at the desired levels, since they do not seem economically worthwhile (del Mar Solà et al., 2021). This situation has been called the energy efficiency gap or energy efficiency paradox (Jaffe and Stavins, 1994). This current paper aims to resolve this paradox for a particular case belonging to a production environment by developing a planning tool to optimize the recovery of energy losses and reduce energy consumption.

From the environmental perspective, besides resolving the aforementioned paradox, energy users must also provide to maintain their systems for a prolonged time. In other words, energy users must develop

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sustainable systems (note that sustainability is the ability to maintain a certain status or process in existing systems (Leonard, 2012)) in the practice. Sustainability is an attractive and up-to-date research field for the research community for the past years due to the growing population and decreasing natural resources. After an advanced search is done on the web of science (WoS) website by using the keyword ‘sustainability’, it is possible to reach more than 180,000 papers since 1971. Besides, if the search is narrowed by the ‘sustainability and ‘energy efficiency’ keywords then it is possible to reach more than 9000 papers since 1991. These two searches on the WoS website put forward the significance and popularity of sustainability for both in general and in energy efficiency considerations. Here, the reader is suggested to read the review papers of Glavič and Lukman (2007), Williams et al. (2017), Olawumi and Chan (2018) and Axon and Darton (2021) on sustainability.

The goal of sustainability is to optimize the resources according to human needs while considering the Economic, Social and Environmental pillars. Having said that, it will not be wrong to indicate that energy efficiency is related to the economic and environmental pillars of sustainability. From this exhibited point of view, industrial companies – one of the main energy consumers in the world – must manage their resources, especially energy, within the context of sustainability and energy efficiency. In other words, the resources must be managed by considering the economic pillar of sustainability, e.g., minimization of the production cost - on one hand, and by considering the environmental pillar of sustainability on the other. Conceptually, companies must manage their energy resources from the “energy sustainability” (Ninno Muniz et al., 2020) point of view. For more detailed information about sustainable energy management in production systems, the reader should refer to the papers of Chen et al. (2013), AlGeddawy and ElMaraghy (2016), Menghi et al. (2019), Jenny et al., (2019), Sola and Mota (2020) and Hasan and Trianni (2020).

From this point of view, it could be said that the heating system of a production plant is the major source of energy waste since it does not constitute a direct cost for a product. On the other hand, in the company, the heating systems should be used to provide a comfortable working environment for both the employees in the offices and the production areas. This situation induces the aforementioned energy efficiency paradox, which must be resolved as effectively as possible, for the production companies, too.

This paper focusing on an energy efficiency paradox aims to minimize the energy consumption used for the heating and cooling system of a production company and to optimize the investment cost of the heat recovery system. While the cooling system decreases the temperature of the oil in the air compressors or hydraulic systems to continue for operation, the heating system comforts the working environment in terms of temperature. In line with this purpose, this contradiction is modelled as an optimization problem and solved to effectively resolve this paradox for a production company and to provide the company with a vision for circular economy, sustainability and energy efficiency.

As a final note, this study, which is a typical application of the circular economy approach, aims to keep products, equipment and infrastructure in use for longer, thus improving the productivity of these resources. Waste materials and energy should become input for other processes: either a component or recovered resource for another industrial process or as regenerative resources for nature. This regenerative approach is in contrast to the traditional linear economy, which has a "take, make, dispose of” model of production (Geissdoerfer et al. (2017), Korhonen et al. (2018), Merli et al. (2018), Geissdoerfer et al. (2020), Yadav et al.,(2020), Pascale et al., (2021), Sarja et al. (2021); Vinante et al. (2021)). According to the European Parliament Briefing (Bourguignon, 2016) any attempt to reduce waste to a minimum is considered within the concept of the circular economy. Therefore, the case handled in this paper – reusing the lost heat in the compressors in the central heating system to heat the necessary rooms in a closed loop – is certainly within the concept of the circular economy. The reader is also suggested to read the review papers about the circular economy (Akhimien et al. (2020); Bressanelli et al. (2021); Cimen (2021); De Oliveira et al. (2021); Di Bartolo et al. (2021); Romero et al. (2021)) and its application to energy issues (Pan et al. (2015); Ingrao et al. (2018); Bist et al. (2020); Mutezo and Mulopo (2021)).

The remainder of this paper is organized as follows. Section 2 describes the material and methods and explains in detail a mixed-integer mathematical model developed. Computational results are given in Section 3 and finally concluding remarks and discussions in Section 4.

2. Material and methods

A brief literature review on heat recovery system optimization (HRS) is given first. Afterwards, this section presents the formal definition of the problem, followed by a mathematical programming formulation explained in detail.

2.1. Literature review

Industrial waste heat recovery systems constitute a widely discussed topic by the research community to resolve such energy efficiency paradoxes. These systems transform the energy produced during industrial waste heat processes and that is not utilized in the process to use for different purposes (Brückner et al., 2015). The research on waste heat recovery systems could be considered twofold; to improve the effectiveness of such systems and integrate these systems into the process industry. The research on waste heat recovery systems could be categorized within two classes as the studies trying to improve the effectiveness of such systems and the studies trying to integrate these systems into the process industry. The reader is suggested to read the review papers of Saghafifar et al. (2019), Omar et al. (2019) and Loni et al. (2021) to be informed on the studies that address to improve the effectiveness of waste heat recovery systems. On the other hand, below we chronically overview the studies on integrating the waste heat recovery systems to the process industry, since the current paper is also on the integration of a heat recovery system to a manufacturing plant.

Ponce-Ortega et al. (2011) formulated an integration problem as a multi-objective mixed-integer linear programming (MILP) model that aimed to minimize the cost as well as the greenhouse gas emissions. Hipólito-Valencia et al. (2013) developed a mixed-integer nonlinear programming (MINLP) model to simultaneously determine the optimal configuration, design parameters and operating conditions for an integration problem. Lira-Barragán et al. (2014a) formulated an integration problem as a multi-objective MINLP model to simultaneously consider the economic, environmental and social dimensions of sustainability. Chen et al. (2014) also formulated an integration problem as an MINLP model and proposed a two-step solution procedure to minimize the external utility consumption and maximize the work produced from waste heat. Lira-Barragán et al. (2014b) proposed a mathematical programming model for an integration problem to maximize the total annual profit, the overall greenhouse gas emissions and the number of jobs that can be created by the use of different types of primary energy sources. Chang et al. (2016) reformulated a non-convex MINLP model of an integration problem considering the distance factor involved with piping and pumping cost as a convex MINLP model. Yu et al. (2017) proposed a two-step method for an integration problem to increase the thermal efficiency and heat recovered by the working fluid while the optimal configuration and operating conditions were determined, and the number of heat exchangers was minimized. Elsido et al. (2019) proposed a novel decomposition algorithm to tackle the challenging MINLP arising from the simultaneous synthesis and design of heat exchanger networks integrated with utility systems. Topolski et al. (2019) developed a mathematical model with the concept of the eco-industrial park and carbon−hydrogen-oxygen symbiosis networks to integrate hydrocarbon processing plants considering the integration of energy and various cycle systems. Wang et al. (2019) figured out the optimization solutions for complex multi-heat source systems. Pina et al.

(2020) formulated an integration problem as a multi-period MILP model that minimizes the total annual cost of installing and operating the system using local-based data. Liu et al. (2020) presented a multi-objective optimization framework considering the dual objectives of the economy and the environment for an integration problem. Sun et al. (2020) proposed an optimization-based method to simultaneously determine the structure and the operating conditions of an integration problem. Xu et al. (2020) developed a multi-objective MINLP for an integration problem that considers the total exergy destruction and the total annual cost as two objectives. López-Flores et al. (2021) proposed metaheuristic−deterministic optimization strategies, which were based on an MINLP, to determine the configuration and operating parameters of the integrated system, considering economic, environmental, and social aspects. Laouid et al. (2021) presented the multi-objective optimization for two cases of an integration problem; the first was the combination of exergy efficiency and electricity production cost, the second was the combination of net output power and electricity production cost.

As the literature review given above clearly indicates, it is projected that the handled problem should be formulated as a cost-based multi-objective optimization problem since designing contradictory cost-based objective functions is a topic hardly studied in the literature. Most studies formulated and optimized the heat recovery systems by considering multi-objectives. However, almost all the studies considered technical matters with cost-based issues to formulate and handle the problem as a multi-objective optimization problem. This current paper considers two conflicting cost-based objective functions as distinct from the related literature. This design of the contradictory objective functions with technical issues and employing Goal Programming as a solution method constitute the main contribution and novelty of the current paper. Apart from technical issues, the obtained results indicate that the developed mathematical programming model is a successful decision support system since its single and multi-objective versions are capable of identifying energy-efficient production designs within the context of the real-life problem on hand and the circular economy.

2.2. Formal problem description

The problem handled within the context of this paper is a design problem to minimize energy used in heating systems of a production plant considering the sustainability, circular economy and energy efficiency points of view. In other words, the problem is to design a system that minimizes the cost of heating systems by achieving minimum energy consumption. Additionally, some additional company-oriented goals must also be considered while achieving that objective.

The production plant has many compressors producing air for pneumatic systems. These compressors use oil to produce air and the oil become warmer during this process. To be able to reuse the same oil during continuous air production, another system is used to decrease the temperature of the warmed oil. Compressors and temperature decreasing systems are being operated cyclically so far as the machines need air for operation. Both the compressors and temperature decreasing systems use energy during operation. It is projected that the energy used by the temperature decreasing system could be avoided and therefore the oil could be cooled in another way that would provide energy efficiency. Instead of using a temperature decreasing system, a system using high-temperature oil to heat water for the central heating system could be installed. Such a system not only provides hot water for the heating system but also decreases the temperature of the oil since the oil loses temperature while heating the water. Another advantage of installing such a system is to avoid the energy used to heat the offices and closed areas within the factory and to use renewable energy for the central heating system. Fig. 1 visualises a production plant for which such a system could be installed. This system is labelled as the “Heat Recovery System” (HRS) as seen in Fig. 1. Installing such a system has an investment cost based on its capacity, which is the number of compressors that might be integrated into the HRS. This investment cost of the HRS does not depend on the types of compressors that could be integrated into the HRS, but their quantity. That is to say, the investment cost of HRS may vary because of the number of compressors assigned to the HRS. To realize this situation within the problem formulation a parameter, S_j, is defined, and it must be mentioned that this cost parameter is independent of the compressor type. For that reason, this parameter is defined as the marginal cost of assigning an extra compressor to the HRS independent of its type.

Having decided to install an HRS that uses the compressors’ hot oil as the input of the central heating system to warm up the water some research questions, which must be handled from an optimization point of view, arise. What capacity for the HRS should be chosen? How many and which compressors should be integrated into this system? How many and which areas should be heated via this system? How should the central heating system be designed, that is, which route should be selected to circulate the water within the central heating system? Of course, these research questions must be resolved with an optimization point of view to provide a cost advantage to the company. That is, a design, which minimizes the cost of compressor cooling and the cost of central heating, must be identified according to the company goals. Fig. 2 visualises such a design for the production plant given in Fig. 1.

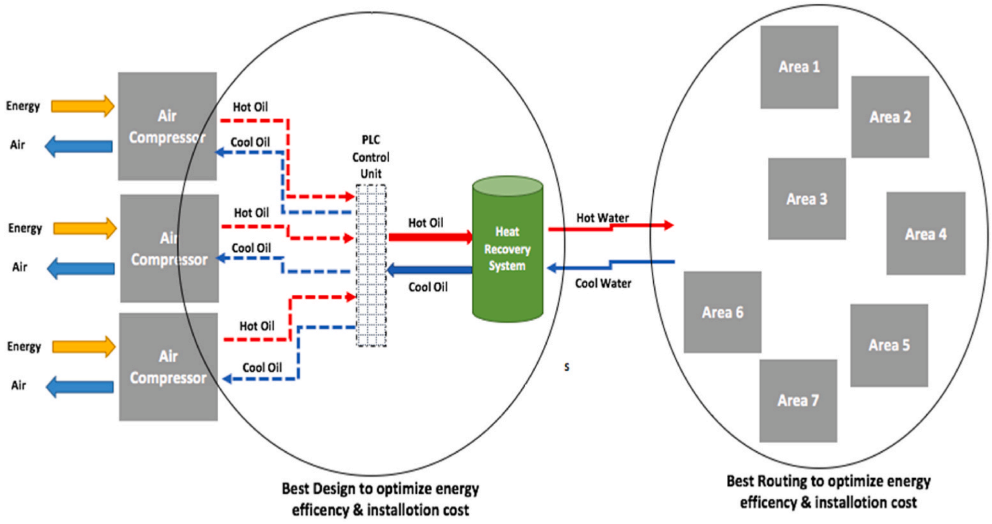

Fig. 1. Visualisation of a production plant using an HRS.

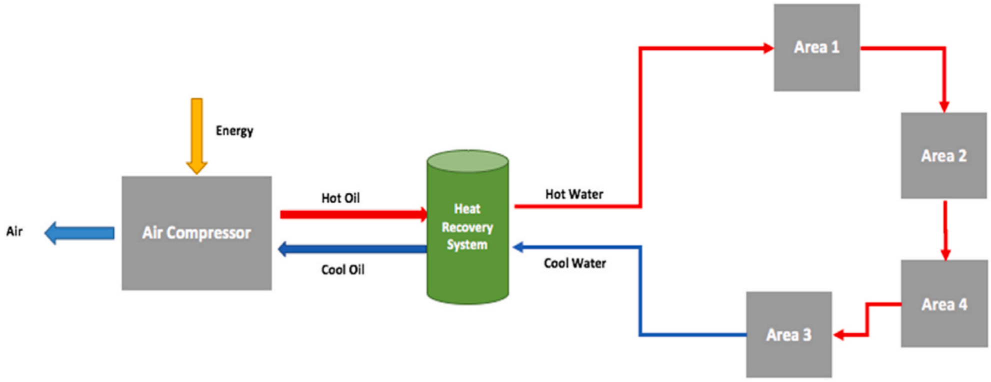

Fig. 2. An example design of the central heating system that uses compressor's hot oil.

By considering the aforementioned research questions, the problem dealt with within the context of this paper must be handled from the optimization point of view. In line with this purpose, the following subsection formulates the related problem as an optimization problem.

2.3. Problem formulation

This subsection formulates the aforementioned design problem as a multi-objective mixed-integer linear programming model. Before describing the formulation in detail, the model's assumptions and notations (Table 1) are stated as follows to provide a clearer understanding.

Table 1
Model notations with their definitions.

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

1. The pipeline of the HRS is started from the HRS and finished in the HRS.
2. Both the HRS and areas must have only one successor and predecessor in the central heating system.
3. Compressor number is always ranked by a descending order according to the energy consumption for the cooling. The bigger compressor is assigned first.
4. At least one compressor and one area are assigned to the system to calculate the optimum return on investment if the heating recovery system is used for energy efficiency.

Besides the objective function, the constraints of the model can be grouped into 3 sets: assignment, routing and extra energy consumption. The objective function and all the constraints sets are explained in detail in the following sub-sections.

2.3.1. Objective function

The objective function is to identify the design with the minimum cost. To achieve this purpose the objective function has four components as given below. The first component minimizes the heating and cooling costs of the areas and the compressors that are assigned to HRS respectively through Eq. (1). Therefore, this first component optimizes the extra cost of cooling down for the compressors and heating up for the areas.

$$Z_1 = \sum_{m=1}^{M} CC_m{}^{*}B_m + \sum_{m=1}^{M} HC_m{}^{*}A_m \tag{1}$$

On the other hand, the areas and compressors that are not assigned to the HRS would of course have some heating and cooling costs. The second part of the objective function aims to minimize these costs through Eq. (2). That is, the second component forces the model to use hot oil to heat as many areas as possible.

$$Z_2 = \sum_{m=1}^{M} \sum_{j=1}^{J} CC_m * D_{jm} * \left(1 - y_j\right) + \sum_{m=1}^{M} \sum_{i=1}^{N} HC_m * E_{im}{}^{*}(1 - x_i) \tag{2}$$

The third part of the objective function calculates the total investment costs for the installations of the heating system such as radiator cost, piping cost between areas, etc through Eq. (3). That is, this component of the objective function minimizes the total fixed investment cost for the areas that are assigned to the HRS.

$$Z_3 = \sum_{i=1}^{N} x_i{}^{*} F_i + \sum_{\substack{k=1 \\ k \neq i}}^{N} \sum_{i=1}^{N} z_{ki}{}^{*}p_{ki} \tag{3}$$

The fourth and the last part of the objective function calculates the total investment cost of the HRS through Eq. (4). Here, S_j, the marginal cost for adding a new compressor to the system is not related to the compressor type but depends on the number of compressors assigned to the HRS. The last component of the objective function thereby minimizes the total marginal cost of compressors added.

$$Z_4 = \sum_{j=1}^{J} y_j * S_j \tag{4}$$

Finally, the summing of all the above-mentioned cost components constitutes the model's objective function (Eq. (5)), which minimizes the total cost to identify the optimum design for HRS's installation.

$$min\ OBJ_1 = Z_1 + Z_2 + Z_3 + Z_4 \tag{5}$$

To plan the installation of the HRS on a cost-effective basis would be incomplete. In other words, the decision-maker must not only consider the cost but also the saving. For that reason, another objective function that aims at maximizing the total saving must also be designed to optimize the installation of HRS and therefore to give a more realistic decision. For the problem on hand, the maximum achievable total saving may be equal to the total cost originated from the yearly energy consumption to heat the areas and to cool down the oil of compressors. That is, the total saving could be achieved if all the compressors and areas are assigned to the HRS, and therefore the maximum achievable total saving could be calculated through Eq. (6).

$$Z_5 = \sum_{m=1}^{M} \sum_{j=1}^{J} CC_m * D_{jm} * y_j + \sum_{m=1}^{M} \sum_{i=1}^{N} HC_m * E_{im} * x_i \tag{6}$$

While designing an objective function to optimize the saving, it must be taken into account that the maximum saving is achievable, if and only if each of the cost values defined by Z_1 & Z_2 is equal to zero. Thus, the saving based objective function, which maximizes the total saving to identify the optimum design for HRS's installation, could be constituted as given by Eq. (7). Here, it must be noted that this objective function does not consider any limitation on the investment cost.

$$max\ OBJ_2 = Z_5 - (Z_1 + Z_2) \tag{7}$$

2.3.2. Assignment constraints

As stated before, as the fourth assumption of the model, at least one compressor and one area must be assigned to the HRS to be able to calculate a return on investment value. This assumption of the model is satisfied through Eq.s 8 and 9. Additionally, area 0 denotes the HRS centre and Eq. (10) ensures the assignment of the HRS centre to the central heating system.

$$\sum_{i=1}^{N} x_i \geq 1 \tag{8}$$

$$\sum_{j=1}^{J} y_j \geq 1 \tag{9}$$

$$x_0 = 1 \tag{10}$$

Due to the compressors type independent nature of the parameter S_j, compressors are ranked according to their energy consumptions in descending order as stated as the third assumption of the model. Because of this assumption, Equation (11) ensures the assignment of the compressors according to their ordered sequence. That is to say, if it is required to incorporate a new compressor into the central heating system, the compressors having lower ranks must be already assigned to the central heating system.

$$y_{j-1} - y_j \geq 0; \quad \forall j \in \{2, \ldots, J\} \tag{11}$$

2.3.3. Routing constraints

Once the compressors and areas that will be assigned to the central heating system are identified, then the pipelines must be designed and installed in a flow-based manner. In other words, a route must be constructed to circulate the hot water within the central heating system, therefore this part of the model refers to the travelling salesman problem (TSP) and the related equations are based on the TSP formulations (Langevin et al., 1990). For that reason, the model has to identify the optimum route of the hot water for the areas assigned to the HRS. According to the second assumption of the model, both the HRS and the areas assigned to the HRS must have only one successor and predecessor in the central heating system, which is ensured through Eqs. (12)–(15). That is, an area and HRS can have only one entrance and one exit for the pipeline. Additionally, there must be unidirectional pipelines between the areas and HRS belonging to the central heating system. Eq. (16) ensures that the design has unidirectional pipelines for the central heating system.

$$\sum_{i=0}^{N} z_{ki} \leq 1 \quad \forall k \in \{0, \ldots, N\} \,\Big|\, k \neq i \tag{12}$$

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

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

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

$$z_{ki} + z_{ik} \leq 1 \quad \forall k, i \in \{0, \ldots, N\} \mid k \neq i \tag{16}$$

2.3.4. Energy consumption constraints

After identifying the areas and compressors assigned to the HRS and constructing the routes, it is required to identify whether extra energy consumption is needed. This extra energy could be used for heating or cooling purposes and the amount of this energy is calculated through Eq. (17). If the temperature of the oil could not be decreased to the desired level after heating the central heating system's water, then an amount of extra energy must be consumed to cool down the oil. For such a situation, the decision variable *B* gets a value greater than 0. On the other hand, if the oil does not rise to the required temperature level to heat the central heating system's water, then an extra amount of energy must be supplied to heat the water. For such a situation, the decision variable *A* gets a value greater than 0 instead of *B*. However, it is ensured that the net energy consumption will be always 0.

$$\sum_{j=0}^{J} D_{jm} * y_j - \sum_{i=0}^{N} E_{im} * x_i + \sum_{i=1}^{N} \sum_{k=1}^{N} L_{kim} * z_{ki} + A_m - B_m = 0; \quad m \in \{1, \ldots, M\} \tag{17}$$

3. Results

This section presents the implementation of the developed mathematical model to a real-life problem and also test the performance of the model on a set of problem instances generated based on the real-life problem. Within this context, the developed model is firstly reformulated as a goal programming model (GP) (Charnes et al., 1955; Charnes and Cooper, 1961) due to its multi-objective structure in the following subsection.

3.1. Goal programming formulation of the developed model

The developed mathematical model is reformulated as a GP model since the GP formulation reduces the complex multi-objective problems to single objective programming models. Therefore, GP has been widely used to handle multi-objective optimization problems (Tamiz et al., 1995). GP introduces non-negative deficiency variables when modelling the extent of violations in goals or in soft constraints which are not required to be rigidly enforced. Hence, in a GP model, the objective function must be reformulated as the minimization of the weighted sum of the deficiency variables to satisfy all goals as accurately as possible (Jones and Tamiz, 2010). The deficiency variables of a GP are generally expressed as d_k^- and d_k^+ ; the amount by which goal k is underachieved or overachieved compared to the optimum solution, respectively. Here it must be noted that d_k^+ and d_k^- are minimized within the objective function of a GP for minimization and maximization objectives respectively.

According to the aforementioned requirements of the GP modelling, two new constraints (Eq.s 18 and 19) are added when converting the developed mathematical model to a GP model. As required in the GP modelling, the objective function is expressed as given by Eq. (20).

$$Z_1 + Z_2 + Z_3 + Z_4 - d_1^+ + d_1^- = OBJ_1 \tag{18}$$

$$Z_5 - (Z_1 + Z_2) - d_2^+ + d_2^- = OBJ_2 \tag{19}$$

$$min\ OBJ_3 = d_1^+ + d_2^- \tag{20}$$

As a result, the reformulation of the developed mathematical model as a GP yields the following formulation.

Objective function (20).

subject to

Constraints (8)–(17) and Constraints (18), (19).

3.2. Application to a real-life problem

This sub-section presents an implementation of the developed multi-objective optimization model to plan an HRS installation for a manufacturing factory. The factory is one of the biggest manufacturing plants of an international company manufacturing products for the global home appliances market and is located in Turkey. There are 3 main production (mechanical, painting, and assembly) flows and office buildings in this plant. This means it is aimed to determine the best design for the decision-makers. The related manufacturing plant has two compressors required to be cooled down and 8 different areas required to heat. Fig. 3 visualises the related production plant for which an HRS is desired to be installed.

The decision on the installation of the HRS for this manufacturing plant is evaluated by using the yearly data. Within this context, the first data set, the monthly energy consumption for heating the areas and cooling down the compressors, induce some monthly costs. Another cost item namely marginal cost arises when integrating the compressors to the HRS. The marginal costs for Compressor1 and Compressor2 are 42,600€ and 44,750€ respectively. Besides these marginal costs of the compressors, fixed investment costs for heating the areas with the HRS must also be taken into consideration. These fixed cost items for 8 areas are 4843€, 7298€, 3500€, 7711€, 8157€, 8990€, 4675€ and 5578€ respectively. Another cost item that must be considered is the piping cost between the areas. This cost item between any two areas may arise if and only if both the areas were integrated into the HRS system and the pipeline connects these two areas. Finally, the last data set is the average energy loss between the areas connected via pipeline. This energy loss is actually due to the temperature decrement of the circulated hot water within the pipeline. Due to the space limitations, the data of the case problem - monthly energy consumption for heating and cooling down (kJ/month), heating & cooling costs for each month per kJ, fixed investment cost for the piping system of the heating system between areas and average energy loss between areas (kJ) – are provided in the Appendix.

This aforementioned real-life problem is solved via the developed mixed-integer linear programming (MILP) formulation. The problem is firstly solved according to the individual objective functions, OBJ1 and OBJ2, then the multi-objective version of the problem formulation is implemented. For the multi-objective version, the model is solved with equal weights (EW) and with normalized weights (NW). For all these implementations the IBM ILOG CPLEX solver was used, and all tests have been conducted on a personal computer running on a 1.1 GHz Dual-Core Intel CPU. Of Course, besides the mentioned objective functions, another key performance indicator (KPI) of the design problem is the return on investment (ROI), since it is a real-life optimization problem. ROI is the efficiency KPI of a project and it is the gain ratio to an investor resulting from an investment of some resources. ROI can be computed by using three financial quantities of (1) revenue, (2) assets, and (3) costs via Eq. (21) as given below (Hopp and Spearman, 2011).

$$ROI = \frac{Revenue - Costs}{Assets} \tag{21}$$

Table 2 represents all the result obtained via the developed mathematical programming formulation for the considered real-life problem and Fig. 4 visualises the four different designs to provide a better understanding. Note that all costs are in Euros (€) and ROI is in years.

From the observations of the results reported in Table 2, it is obvious that the MILP model with objective 1, GP model with EW and GP model with NW provide the same results and therefore the same configurations. It is concluded that, if the main concern of the decision-maker is the ROI then the selection of the configuration obtained via MILP model with objective 1, GP model with EW and GP model with NW is rational since they provide a solution with an ROI equal to 1.49. In other words,

Table 2
Results of the case study.

Objective Function	Case Study - 2 Compressor +8 Areas			
	MILP Model Objective - 1	MILP Model Objective - 2	GP Model Objective - EW	GP Model Objective - NW
Z1	15,812	28,873	15,812	15,812
Z2	43,094	0	43,094	43,094
Z3	15,279	64,366	15,279	15,279
Z4	42,960	132,100	42,960	42,960
Z5	97,876	97,876	97,876	97,876
Total Saving	38,970	69,003	38,970	38,970
Total Investment	58,239	196,466	58,239	58,239
ROI	1.49	2.85	1.49	1.49

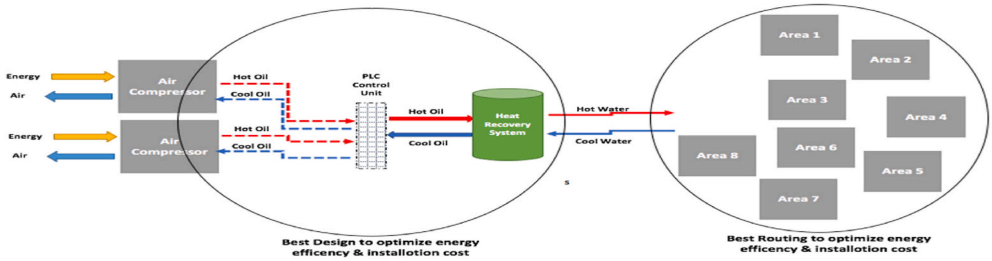

Fig. 3. Visualisation of the production plant.

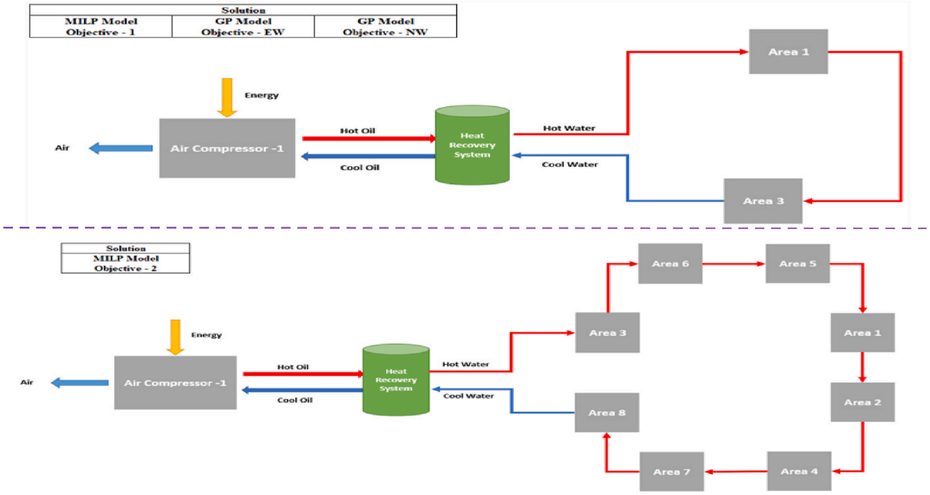

Fig. 4. Visualisation of the real-life problem's solution.

if this configuration is selected then the HRS system will amortize itself within 1.49 years. On the other, if the main concern of the decision-maker is to install a greener production plant, then it is suggested to select the configuration identified via the MILP model with objective 2, although it provides a solution with an ROI equal to 2.85.

3.3. Performance evaluation of the MILP model

This sub-section presents the performance evaluation test of the developed mixed-integer programming formulation on a set of randomly generated problems based on the real-life problem. To be realistic, the problem sizes designated should be as encountered in real-life cases. In line with this purpose, 2, 4, 6, 8 and 10 compressors were mixed up with 5, 10, 15, 20 and 25 areas, and therefore 25 different problems were obtained. All the other data are randomly generated from the uniform distribution. This problem set is solved via the developed mixed-integer linear programming model with a single objective as well as with multiple objectives as it has been done for the real case problem and the obtained results are reported in Appendix in Tables A5, A6, A7, A8 and A9.

From the computational results, it is concluded that the developed mathematical programming model can solve the problem concerned within the context of this paper effectively. The mathematical programming model is capable of identifying different configurations for the related problem through its single objective and multi-objective versions. Hence, it will not be wrong to claim that the developed mathematical model can be used as a decision support system when designing energy-efficient production systems within the context of the handled real-life problem and therefore circular economy. Additionally, to provide a better understanding of the computational effort of the developed mathematical programming model the obtained results for the 26 cases are visualized through Figs. 5–7. Figs. 5 and 6 visualize the trends of ROI and saving for the single and multi-objective versions of the mathematical programming model while Fig. 7 visualises the trend of yearly savings which is equal to *Saving* / *ROI*.

From Fig. 5, it is concluded that the GP with EW was able to provide fewer ROIs than the others on average. Namely, if the main concern is the ROI, then the goal programming implementation of the developed mathematical model with EW – multi-objective version – has the best potential to identify better results in comparison to other options. Besides, the developed mathematical model with OBJ2 – single objective version – produced better savings in comparison to the others on average as can be seen in Fig. 6. In other words, OBJ2 may be selected as the objective function of the developed mathematical model while optimizing the handled problem, if the main concern is the total saving. On the other hand, if the decision-maker would like to make a final decision by considering both the ROI and saving, a new key performance indicator could be suggested as *Yearly Saving* = *Saving* / *ROI*. This new KPI calculates savings per year relative to the ROI. Fig. 7 indicates that the goal programming implementation of the developed mathematical model with NW – multi-objective version – is the best option if the main concern is the Yearly Saving.

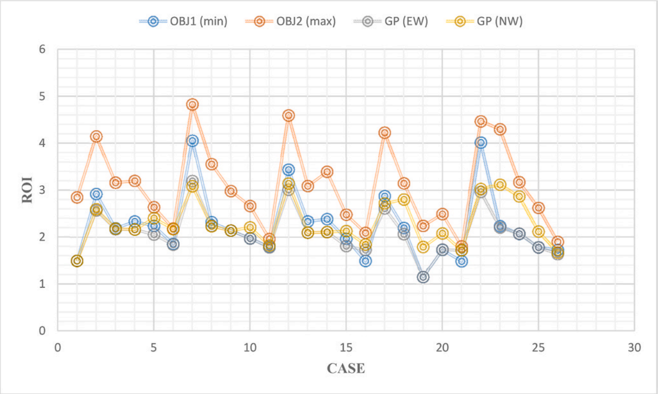

Fig. 5. Trend of ROI

4. Discussion

This paper is concerned with a real-life energy-efficient system design problem within the context of the circular economy. The problem was first formulated as an optimization problem using a mixed-integer linear programming model, that is, the problem was formally described through the mathematical programming approach. Then, the developed model was reformulated as a multi-objective optimization problem using the goal programming approach. Next, a real-life design problem was solved via the single objective and multi-objective versions of the developed mathematical programming model while considering cost minimization and saving maximization. Additionally, the obtained design configurations were evaluated in terms of the return on investment criterion. By doing so, different design configurations were provided to the decision-maker and therefore the developed model could balance investment cost and return on investment. In other words, the developed model can identify green production designs which yield reasonable times for the return on investment. Finally, the capability of the mathematical programming model was tested on a set of randomly

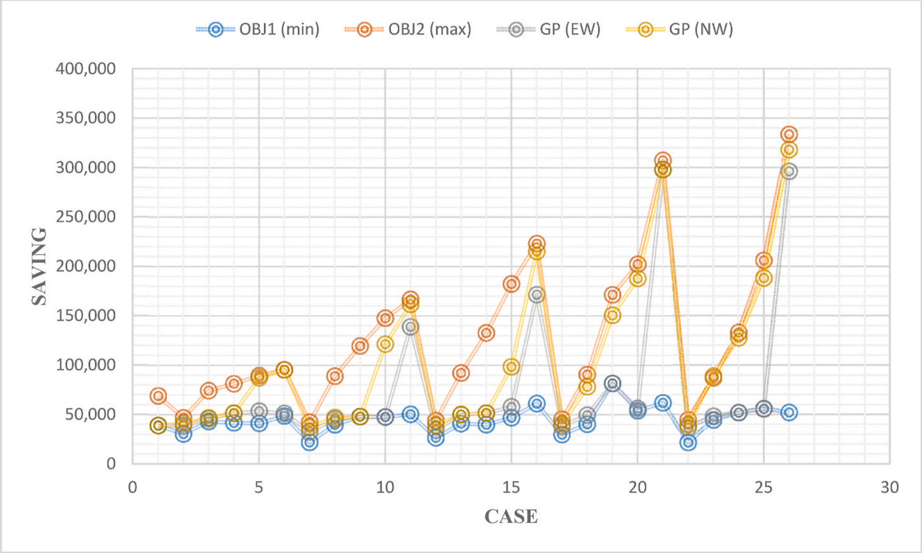

Fig. 6. Trend of saving.

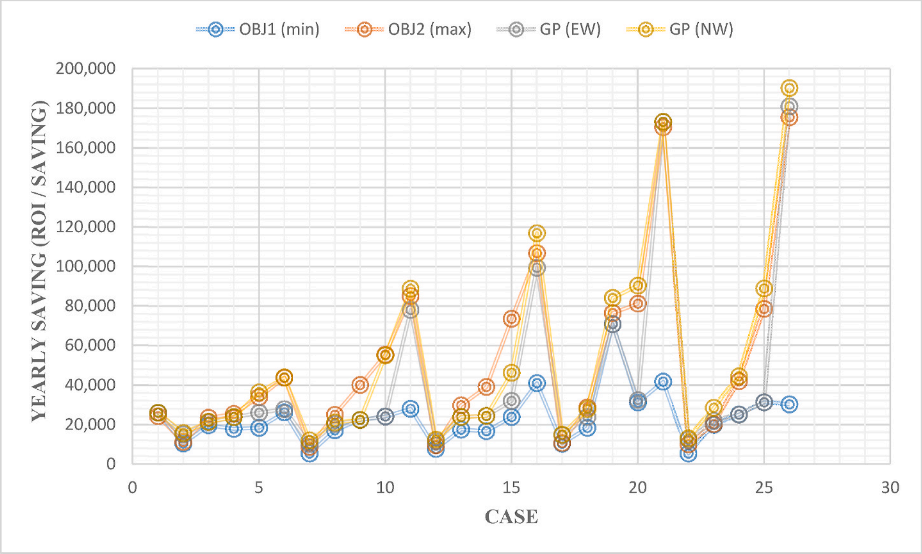

Fig. 7. Trend of yearly saving.

generated problems. The mathematical programming model solved the problem effectively in terms of total investment, total saving and ROI and identified different configurations through its single objective and multi-objective versions. These different configurations have provided the decision-maker flexibility when giving the final decision. The flexibility here refers to the options of the considerations of ROI or installing a greener production plant when selecting the final design of the production plant. As a result, it is concluded that the developed mathematical programming model is a strong decision support tool that could be used while designing energy-efficient production systems within the context of the concerned real-life problem and for sustainability and circular economy problems to evaluate the best solutions before making a final decision.

For future research, the developed mathematical programming model might be extended by including different energy-efficient design problems within the production plants. These design problems might be about the energy consumptions for heating or cooling after the standard production process such as hydraulic presses, chimneys of the industrial ovens, or heating industrial ovens. On the other hand, it was only considered the energy consumption minimization for two pillars of Sustainability Management in this paper; environmental sustainability by optimizing energy consumption and economical sustainability by minimizing investment cost. The developed mathematical programming model may be extended by adding social sustainability-related objectives to optimize all pillars of sustainability.

CRediT authorship contribution statement

S. Serhat Karakutuk: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Sener Akpinar:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **M. Arslan Ornek:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1
Monthly Energy Consumption for Heating Up & Cooling Down (kJ/month)

Month	Energy Consumption for Cooling Down - kJ/month		Energy Consumption for Heating Up - kJ/month							
	Comp.1	Comp.2	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
1	145,745,456	111,227,456	201,618,592	49,287,520	63,161,664	30,990,888	58,697,336	55,103,280	4,773,944	15,895,016
2	145,745,456	111,227,456	201,618,592	49,287,520	63,161,664	30,990,888	58,697,336	55,103,280	4,773,944	15,895,016
3	105,997,456	80,893,456	126,013,712	30,806,792	39,476,040	19,371,920	36,685,312	34,442,688	2,983,192	9,937,000
4	119,244,000	91,002,000	75,609,064	18,484,912	23,685,624	11,623,152	22,012,024	20,664,776	1,790,752	5,962,200
5	145,745,456	111,227,456	75,609,064	18,484,912	23,685,624	11,623,152	22,012,024	20,664,776	1,790,752	5,962,200
6	158,992,000	121,336,000	0	0	0	0	0	0	0	0
7	92,746,728	70,780,728	0	0	0	0	0	0	0	0
8	79,496,000	60,668,000	0	0	0	0	0	0	0	0
9	119,244,000	91,002,000	75,609,064	18,484,912	23,685,624	11,623,152	22,012,024	20,664,776	1,790,752	5,962,200
10	158,992,000	121,336,000	126,013,712	30,806,792	39,476,040	19,371,920	36,685,312	34,442,688	2,983,192	9,937,000
11	145,745,456	111,227,456	126,013,712	30,806,792	39,476,040	19,371,920	36,685,312	34,442,688	2,983,192	9,937,000
12	172,242,728	131,448,728	201,618,592	49,287,520	63,161,664	30,990,888	58,697,336	55,103,280	4,773,944	15,895,016

Table A2
Heating & Cooling Costs for each month per kJ

Month	Heating Cost	Cooling Cost	Month	Heating Cost	Cooling Cost
1	1.91E-05	1.63E-05	**7**	1.63E-05	1.91E-05
2	1.91E-05	1.63E-05	**8**	1.63E-05	1.91E-05
3	1.82E-05	1.72E-05	**9**	1.72E-05	1.82E-05
4	1.72E-05	1.82E-05	**10**	1.82E-05	1.72E-05
5	1.72E-05	1.82E-05	**11**	1.82E-05	1.72E-05
6	1.63E-05	1.91E-05	**12**	1.91E-05	1.63E-05

Table A3
Fixed Investment Cost for Piping System of the Heating System between Areas

Piping Cost		To Area								
		0	1	2	3	4	5	6	7	8
From Area	**0**	0	2613	1365	2115	2805	1563	1890	1848	1080
	1	2613	0	1062	2208	2670	1371	2181	2115	1752
	2	1365	1062	0	1452	1176	2940	2904	1896	2472
	3	2115	2208	1452	0	2946	2781	1893	2133	2082
	4	2805	2670	1176	2946	0	2937	1839	1506	1773
	5	1563	1371	2940	2781	2937	0	1659	2346	2676
	6	1890	2181	2904	1893	1839	1659	0	1944	2778
	7	1848	2115	1896	2133	1506	2346	1944	0	1752
	8	1080	1752	2472	2082	1773	2676	2778	1752	0

Table A4
Average Energy Loss between Areas (kJ)

AREA		FROM/TO									AREA		FROM/TO								
		0	1	2	3	4	5	6	7	8			0	1	2	3	4	5	6	7	8
MONTH - 1	**0**	**0**	548	289	444	590	331	397	389	226	**MONTH - 2**	**0**	**0**	548	289	444	590	331	397	389	226
	1	548	**0**	226	464	561	289	460	444	368		**1**	548	**0**	226	464	561	289	460	444	368
	2	289	226	**0**	305	247	615	611	397	519		**2**	289	226	**0**	305	247	615	611	397	519
	3	444	464	305	**0**	619	586	397	448	439		**3**	444	464	305	**0**	619	586	397	448	439
	4	590	561	247	619	**0**	615	385	318	372		**4**	590	561	247	619	**0**	615	385	318	372
	5	331	289	615	586	615	**0**	347	494	561		**5**	331	289	615	586	615	**0**	347	494	561
	6	397	460	611	397	385	347	**0**	410	582		**6**	397	460	611	397	385	347	**0**	410	582
	7	389	444	397	448	318	494	410	**0**	368		**7**	389	444	397	448	318	494	410	**0**	368
	8	226	368	519	439	372	561	582	368	**0**		**8**	226	368	519	439	372	561	582	368	**0**
MONTH - 3	**0**	**0**	276	146	222	297	167	201	197	113	**MONTH - 4**	**0**	**0**	159	84	130	172	96	113	113	67
	1	276	**0**	113	234	280	146	230	222	184		**1**	159	**0**	67	134	163	84	134	130	109
	2	146	113	**0**	155	126	310	305	201	259		**2**	84	67	**0**	88	71	176	176	117	151
	3	222	234	155	**0**	310	293	201	226	222		**3**	130	134	88	**0**	180	167	117	130	126
	4	297	280	126	310	**0**	310	192	159	188		**4**	172	163	71	180	**0**	176	113	92	109
	5	167	146	310	293	310	**0**	176	247	280		**5**	96	84	176	167	176	**0**	100	142	163
	6	201	230	305	201	192	176	**0**	205	293		**6**	113	134	176	117	113	100	**0**	117	167
	7	197	222	201	226	159	247	205	**0**	184		**7**	113	130	117	130	92	142	117	**0**	109
	8	113	184	259	222	188	280	293	184	**0**		**8**	67	109	151	126	109	163	167	109	**0**
MONTH - 5	**0**	**0**	113	59	92	121	67	79	79	46	**MONTH - 6**	**0**	**0**	0	0	0	0	0	0	0	0
	1	113	**0**	46	96	113	59	92	92	75		**1**	0	**0**	0	0	0	0	0	0	0
	2	59	46	**0**	63	50	126	126	79	105		**2**	0	0	**0**	0	0	0	0	0	0
	3	92	96	63	**0**	126	117	79	92	88		**3**	0	0	0	**0**	0	0	0	0	0
	4	121	113	50	126	**0**	126	79	67	75		**4**	0	0	0	0	**0**	0	0	0	0
	5	67	59	126	117	126	**0**	71	100	113		**5**	0	0	0	0	0	**0**	0	0	0
	6	79	92	126	79	79	71	**0**	84	117		**6**	0	0	0	0	0	0	**0**	0	0
	7	79	92	79	92	67	100	84	**0**	75		**7**	0	0	0	0	0	0	0	**0**	0
	8	46	75	105	88	75	113	117	75	**0**		**8**	0	0	0	0	0	0	0	0	**0**
MONTH - 7	**0**	**0**	0	0	0	0	0	0	0	0	**MONTH - 8**	**0**	**0**	0	0	0	0	0	0	0	0
	1	0	**0**	0	0	0	0	0	0	0		**1**	0	**0**	0	0	0	0	0	0	0
	2	0	0	**0**	0	0	0	0	0	0		**2**	0	0	**0**	0	0	0	0	0	0
	3	0	0	0	**0**	0	0	0	0	0		**3**	0	0	0	**0**	0	0	0	0	0
	4	0	0	0	0	**0**	0	0	0	0		**4**	0	0	0	0	**0**	0	0	0	0
	5	0	0	0	0	0	**0**	0	0	0		**5**	0	0	0	0	0	**0**	0	0	0
	6	0	0	0	0	0	0	**0**	0	0		**6**	0	0	0	0	0	0	**0**	0	0
	7	0	0	0	0	0	0	0	**0**	0		**7**	0	0	0	0	0	0	0	**0**	0
	8	0	0	0	0	0	0	0	0	**0**		**8**	0	0	0	0	0	0	0	0	**0**
MONTH - 9	**0**	**0**	113	59	92	121	67	79	79	46	**MONTH - 10**	**0**	**0**	159	84	130	172	96	113	113	67
	1	113	**0**	46	96	113	59	92	92	75		**1**	159	**0**	67	134	163	84	134	130	109
	2	59	46	**0**	63	50	126	126	79	105		**2**	84	67	**0**	88	71	176	176	117	151
	3	92	96	63	**0**	126	117	79	92	88		**3**	130	134	88	**0**	180	167	117	130	126
	4	121	113	50	126	**0**	126	79	67	75		**4**	172	163	71	180	**0**	176	113	92	109
	5	67	59	126	117	126	**0**	71	100	113		**5**	96	84	176	167	176	**0**	100	142	163
	6	79	92	126	79	79	71	**0**	84	117		**6**	113	134	176	117	113	100	**0**	117	167
	7	79	92	79	92	67	100	84	**0**	75		**7**	113	130	117	130	92	142	117	**0**	109
	8	46	75	105	88	75	113	117	75	**0**		**8**	67	109	151	126	109	163	167	109	**0**
MONTH - 11	**0**	**0**	276	146	222	297	167	201	197	113	**MONTH - 12**	**0**	**0**	548	289	444	590	331	397	389	226
	1	276	**0**	113	234	280	146	230	222	184		**1**	548	**0**	226	464	561	289	460	444	368
	2	146	113	**0**	155	126	310	305	201	259		**2**	289	226	**0**	305	247	615	611	397	519
	3	222	234	155	**0**	310	293	201	226	222		**3**	444	464	305	**0**	619	586	397	448	439
	4	297	280	126	310	**0**	310	192	159	188		**4**	590	561	247	619	**0**	615	385	318	372
	5	167	146	310	293	310	**0**	176	247	280		**5**	331	289	615	586	615	**0**	347	494	561
	6	201	230	305	201	192	176	**0**	205	293		**6**	397	460	611	397	385	347	**0**	410	582
	7	197	222	201	226	159	247	205	**0**	184		**7**	389	444	397	448	318	494	410	**0**	368
	8	113	184	259	222	188	280	293	184	**0**		**8**	226	368	519	439	372	561	582	368	**0**

Table A5
Solution of the Case Studies Part 1–2 Compressors

CASE	1 (2 Compressor + 5 Areas)		2 (2 Compressor + 10 Areas)		3 (2 Compressor + 15 Areas)		4 (2 Compressor + 20 Areas)		5 (2 Compressor + 25 Areas)	
Objective Function	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2
Z1	12,809	24,735	6332	16,447	6897	20,051	7375	15,025	4238	15,817
Z2	28,193	0	42,186	882	62,585	9880	91,516	35,556	145,630	87,250
Z3	29,204	59,236	34,324	99,844	37,402	125,120	32,235	101,110	30,167	73,209
Z4	60,000	135,000	60,000	135,000	60,000	135,000	60,000	135,000	60,000	135,000
Z5	71,564	71,564	91,619	91,619	111,220	111,220	140,090	140,090	198,480	198,480
Total Saving	30,562	46,829	43,101	74,290	41,738	81,289	41,199	89,509	48,612	95,413
Total Investment	89,204	194,236	94,324	234,844	97,402	260,120	92,235	236,110	90,167	208,209
ROI	**2.92**	**4.15**	**2.19**	**3.16**	**2.33**	**3.20**	**2.24**	**2.64**	**1.85**	**2.18**
Objective Function	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**
Z1	8018	7661	5023	4680	5042	5042	6847	7568	4290	15,847
Z2	24,600	22,803	40,715	40,127	54,651	54,651	79,711	45,202	142,930	87,250
Z3	40,056	46,658	39,497	42,076	51,428	51,428	50,082	74,951	34,298	71,978
Z4	60,000	60,000	60,000	60,000	60,000	60,000	60,000	135,000	60,000	135,000
Z5	71,564	71,564	91,619	91,619	111,220	111,220	140,090	140,090	198,480	198,480
Total Saving	38,946	41,100	45,881	46,812	51,527	51,527	53,532	87,320	51,261	95,383
Total Investment	100,056	106,658	99,497	102,076	111,428	111,428	110,082	209,951	94,298	206,978
ROI	**2.57**	**2.60**	**2.17**	**2.18**	**2.16**	**2.16**	**2.06**	**2.40**	**1.84**	**2.17**

Table A6
Solution of the Case Studies Part 2–4 Compressors

CASE	6 (4 Compressor + 5 Areas)		7 (4 Compressor + 10 Areas)		8 (4 Compressor + 15 Areas)		9 (4 Compressor + 20 Areas)		10 (4 Compressor + 25 Areas)	
Objective Function	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2
Z1	16,707	33,926	7911	46,689	4259	34,550	4597	38,302	4183	31,160
Z2	75,245	38,203	87,987	0	101,890	0	134,840	1188	192,940	49,656
Z3	29,396	69,533	32,172	126,450	42,658	166,610	34,115	203,080	30,318	136,430
Z4	60,000	135,000	60,000	190,000	60,000	190,000	60,000	190,000	60,000	190,000
Z5	114,000	114,500	135,660	135,660	154,140	154,140	187,120	187,120	247,440	247,440
Total Saving	22,048	42,371	39,762	88,971	47,991	119,590	47,683	147,630	50,317	166,624
Total Investment	89,396	204,533	92,172	316,450	102,658	356,610	94,115	393,080	90,318	326,430
ROI	**4.05**	**4.83**	**2.32**	**3.56**	**2.14**	**2.98**	**1.97**	**2.66**	**1.79**	**1.96**
Objective Function	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**
Z1	11,417	9934	5238	5237	4259	4259	4597	17,599	11,707	17,052
Z2	70,350	67,456	84,942	83,282	101,890	101,890	134,840	48,055	96,758	68,689
Z3	44,594	54,478	41,834	45,248	42,658	42,658	34,115	103,200	82,388	99,539
Z4	60,000	60,000	60,000	60,000	60,000	60,000	60,000	165,000	165,000	195,000
Z5	114,500	114,500	135,660	135,660	154,140	154,140	187,120	187,120	247,440	247,440
Total Saving	32,733	37,110	45,480	47,141	47,991	47,991	47,683	121,466	138,975	161,699
Total Investment	104,594	114,478	101,834	105,248	102,658	102,658	94,115	268,200	247,388	294,539
ROI	**3.20**	**3.08**	**2.24**	**2.23**	**2.16**	**2.16**	**1.97**	**2.21**	**1.78**	**1.82**

Table A7
Solution of the Case Studies Part 3–6 Compressors

CASE	11 (6 Compressor + 5 Areas)		12 (6 Compressor + 10 Areas)		13 (6 Compressor + 15 Areas)		14 (6 Compressor + 20 Areas)		15 (6 Compressor + 25 Areas)	
Objective Function	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2
Z1	14,450	32,721	4939	28,358	9582	63,318	7238	45,578	4491	57,324
Z2	111,980	76,406	129,700	55,101	146,580	0	173,880	0	231,040	16,243
Z3	31,655	66,989	35,630	119,650	35,100	205,390	31,961	207,060	31,317	221,550
Z4	60,000	135,000	60,000	165,000	60,000	245,000	60,000	245,000	60,000	245,000
Z5	153,080	153,080	175,610	175,610	196,056	196,056	227,965	227,965	296,763	296,763
Total Saving	26,650	43,953	40,971	92,151	39,894	132,738	46,848	182,387	61,233	223,196
Total Investment	91,655	201,989	95,630	284,650	95,100	450,390	91,961	452,060	91,317	466,550
ROI	**3.44**	**4.60**	**2.33**	**3.09**	**2.38**	**3.39**	**1.96**	**2.48**	**1.49**	**2.09**
Objective Function	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**
Z1	10,190	9489	4900	4900	4215	4215	5432	9846	18,549	34,302
Z2	108,270	104,320	120,640	120,640	140,250	140,250	164,590	119,610	106,690	47,214
Z3	44,221	63,399	44,900	44,900	48,757	48,757	44,832	74,655	101,050	151,330
Z4	60,000	60,000	60,000	60,000	60,000	60,000	60,000	135,000	195,000	245,000
Z5	153,080	153,080	175,610	175,610	196,056	196,056	227,965	227,965	296,763	296,763
Total Saving	34,620	39,271	50,070	50,070	51,591	51,591	57,943	98,509	171,524	215,247
Total Investment	104,221	123,399	104,900	104,900	108,757	108,757	104,832	209,655	296,050	396,330
ROI	**3.01**	**3.14**	**2.10**	**2.10**	**2.16**	**2.16**	**1.81**	**2.13**	**1.73**	**1.84**

Table A8
Solution of the Case Studies Part 4–8 Compressors

CASE	16 (8 Compressor + 5 Areas)		17 (8 Compressor + 10 Areas)		18 (8 Compressor + 15 Areas)		19 (8 Compressor + 20 Areas)		20 (8 Compressor + 25 Areas)	
Objective Function	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2
Z1	13,457	32,613	8844	36,812	4201	65,794	4205	90,561	5120	78,214
Z2	202,080	167,510	217,780	139,590	235,140	83,753	262,700	27,918	318,470	0
Z3	25,868	56,435	28,677	120,130	33,715	168,660	33,216	241,670	32,076	269,120
Z4	60,000	135,000	60,000	165,000	60,000	215,000	60,000	262,500	60,000	285,000
Z5	245,408	245,408	267,020	267,020	320,855	320,855	320,855	320,855	385,595	385,595
Total Saving	29,871	45,285	40,396	90,618	81,514	171,308	53,950	202,376	62,005	307,381
Total Investment	85,868	191,435	88,677	285,130	93,715	383,660	93,216	504,170	92,076	554,120
ROI	**2.87**	**4.23**	**2.20**	**3.15**	**1.15**	**2.24**	**1.73**	**2.49**	**1.48**	**1.80**
Objective Function	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**
Z1	9104	9426	5490	18,593	4201	24,984	4331	46,837	78,518	78,518
Z2	197,880	195,420	212,040	170,230	235,140	145,240	260,300	86,155	8934	8934
Z3	40,390	50,298	42,136	84,157	33,715	104,670	37,373	175,390	228,030	228,030
Z4	60,000	60,000	60,000	135,000	60,000	165,000	60,000	215,000	285,000	285,000
Z5	245,408	245,408	267,020	267,020	320,855	320,855	320,855	320,855	385,595	385,595
Total Saving	38,424	40,562	49,490	78,197	81,514	150,631	56,224	187,863	298,143	298,143
Total Investment	100,390	110,298	102,136	219,157	93,715	269,670	97,373	390,390	513,030	513,030
ROI	**2.61**	**2.72**	**2.06**	**2.80**	**2.16**	**2.16**	**1.73**	**2.08**	**1.72**	**1.72**

Table A9
Solution of the Case Studies Part 5–10 Compressors

CASE	21 (10 Compressor + 5 Areas)		22 (10 Compressor + 10 Areas)		23 (10 Compressor + 15 Areas)		24 (10 Compressor + 20 Areas)		25 (10 Compressor + 25 Areas)	
Objective Function	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2	MILP Model Objective - 1	MILP Model Objective - 2
Z1	17,298	32,866	6661	119,810	4319	70,608	4181	116,520	5608	104,340
Z2	261,780	223,340	272,420	116,700	287,100	139,590	318,440	55,835	380,270	0
Z3	28,005	70,176	39,695	134,800	47,977	207,980	39,712	256,070	30,195	309,780
Z4	60,000	130,000	60,000	240,000	60,000	215,000	60,000	285,000	60,000	325,000
Z5	300,997	300,997	323,715	323,715	343,554	343,554	378,554	378,554	438,172	438,172
Total Saving	21,919	44,791	44,635	87,205	52,135	133,356	55,933	206,199	52,294	333,832
Total Investment	88,005	200,176	99,695	374,800	107,977	422,980	99,712	541,070	90,195	634,780
ROI	**4.02**	**4.47**	**2.23**	**4.30**	**2.07**	**3.17**	**1.78**	**2.62**	**1.72**	**1.90**
Objective Function	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**	**Goal Model Objective - EW**	**Goal Model Objective - NW**
Z1	9636	9419	5069	38,966	4319	48,264	4183	46,867	74,548	89,746
Z2	254,690	251,950	270,250	195,660	287,130	167,510	318,440	143,280	67,148	30,181
Z3	48,772	60,000	46,642	112,760	47,977	171,450	39,712	184,150	200,530	227,140
Z4	60,000	60,000	60,000	165,000	60,000	195,000	60,000	215,000	285,000	305,000
Z5	300,997	300,997	323,715	323,715	343,554	343,554	378,554	378,554	438,172	438,172
Total Saving	36,671	39,628	48,396	89,089	52,105	127,780	55,931	188,407	296,476	318,245
Total Investment	108,772	120,000	106,642	277,760	107,977	366,450	99,712	399,150	485,530	532,140
ROI	**2.97**	**3.03**	**2.20**	**3.12**	**2.16**	**2.16**	**1.78**	**2.12**	**1.64**	**1.67**

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