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Dynamic Modelling and Optimisation of Heat Exchange Networks for Enhanced Energy Efficiency in Industrial Processes

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Abstract

Industrial heat exchanger networks often suffer from suboptimal energy performance due to static design approaches that overlook real-time thermal dynamics. This study addresses this problem by integrating dynamic modeling with genetic algorithm-based optimization to enhance energy efficiency. The proposed method captures realistic heat transfer behavior and optimizes system configurations to minimize energy consumption and heat loss. Simulation results demonstrate energy savings of 23%–25% compared to conventional designs, while also reducing the number of required heat exchange units, leading to lower investment and operational costs. Applied across chemical, oil and gas, and manufacturing sectors, this approach achieves 10%–15% higher energy savings than traditional optimization methods. Furthermore, for existing networks, operational adjustments based on this method provide additional savings of up to 20%–25%. These findings confirm the effectiveness of combining dynamic modeling and optimization for both new designs and retrofitting existing systems, offering a practical solution to improve industrial energy performance.

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1. Introduction

Energy efficiency is essential in modern industry, considering the increasing global energy demand and its environmental impact. According to the International Energy Agency (IEA), the industrial sector accounts for more than 30% of global energy consumption. Therefore, efficient energy management is an economic strategy and a critical step in reducing greenhouse gas emissions. One of the most effective approaches is to improve the efficiency of heat exchange networks, which serve as the main components in thermal energy transfer in various industrial processes. Heat exchange networks are vital in reducing energy waste by reusing available waste heat. The "pinch analysis" method, introduced as an essential strategy in designing heat exchanger networks, has become the basis for many subsequent studies (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Bonhivers, Moussavi, Alva-Argaez, & Stuart, 2016; B.-H. Li, Chota Castillo, & Chang, 2019; Pavão, Caballero, Ravagnani, & Costa, 2020). However, technological developments and the complexity of modern processes require a more dynamic approach to cope with fluctuations in operating conditions and improve performance in real-time.

However, modelling the dynamics of heat exchange networks is challenging because it involves complex interactions between thermodynamic parameters, physical design, and operational control. For example, static approaches often fail to capture significant dynamic changes, such as heat load fluctuations or fluid property changes, as demonstrated in a study by (Alobaid et al., 2017; Erdiwansyah et al., 2020; Yana, Mufti, Hasiany, Viena, & Mahyudin, 2025; Yu et al., 2025). Modelling that does not consider dynamic factors can reduce the overall network efficiency, especially under non-ideal operating conditions, as highlighted in a study (Dupont, Carvalho, Jucá, & Neto, 2019; Huang et al., 2019; Yana et al., 2025). Furthermore, optimising heat exchange networks for better energy efficiency remains a primary research focus. Evolutionary algorithms are used to generate optimal designs in some studies, such as those conducted by (Dai, Li, Zhang, & Zhang, 2023; Mufti, Irhamni, & Darnas, 2025; J. Wang et al., 2025; Zhao, Zhang, Xu, & Leng, 2025). However, these approaches are often limited to certain initial conditions and are difficult to apply to systems that experience continuous operational changes. Therefore, dynamic modeling and optimization integration is needed to generate adaptive and efficient solutions.

This paper aims to develop a dynamic model that can map the behaviour of a heat exchanger network in real time while integrating optimization methods to improve energy efficiency. Unlike previous studies focusing primarily on static aspects or separate optimization, this study will combine both approaches into a comprehensive framework. The novelty of this study lies in the use of modern optimization algorithms, such as artificial intelligence-based algorithms, combined with dynamic models based on partial differential equations. The hybrid approach proposed has shown promising results in the context of single heat exchanger design (Gani et al., 2025; Mahdi, Lohrasbi, & Nsofor, 2019; Rosdi, Erdiwansyah, Ghazali, & Mamat, 2025; Zhang, Li, & Yan, 2024). However, its application to more complex networks still require further exploration. This study seeks to address this need by applying an innovative approach on a broader and more complex scale.

2. Literature Review

Dynamic models in heat exchanger networks describe the real-time thermal interactions between various units in the system. Early research used a static approach in network design, assuming constant operating conditions, as shown by (J. Liu & Zhou, 2016; X. Liu, Liu, Chen, & Hanzo, 2019; Maghfirah, Yusop, & Zulkifli, 2025). Although adequate for initial design, this approach can capture heat load fluctuations, fluid property changes, or transient conditions often occurring in industrial processes. In contrast, dynamic models based on partial differential equations (PDEs) offer the ability to predict system behavior more accurately under changing conditions (Irhamni, Kurnianingtyas, Muhtadin, Bahagia, & Yusop, 2025; H. Li, Shi, & Li, 2024; Raissi & Karniadakis, 2018). However, implementing this model requires complex data processing and often requires high-level computation, so its application on an industrial scale is still limited. The main challenge in modelling the dynamics of heat exchanger networks is handling the complex interactions between thermodynamic aspects, physical design, and operational constraints. For example, a mathematical model for network optimization was developed, but it did not consider time a critical variable (Chupradit et al., 2022; Selvakumar, Maawa, & Rusiyanto, 2025). Furthermore, integrating dynamic models and operational control can help overcome sudden changes, such as disturbances in fluid flow or inlet temperature variations (Imran, Pili, Usman, & Haglind, 2020). However, challenges remain in validating dynamic models with accurate data, especially for highly complex systems with many heat exchangers. Therefore, current research focuses on developing models that are not only mathematically accurate but also practically implementable in industrial energy system control.

Heat exchanger network optimization has been widely studied to improve energy efficiency in various industrial processes. Deterministic algorithms, such as linear programming (LP) and nonlinear programming (NLP), are often used for optimization and were first introduced in the form of pinch analysis by (Bogataj, Klemeš, & Kravanja, 2023; Khalisha, Caisarina, & Fakhrana, 2025). Although these methods can provide optimal solutions under constant operating conditions, they tend to be limited when dealing with dynamic or complex systems with many variables. For example, nonlinear programming was used for heat exchanger network optimization, but the assumption of stable operating conditions significantly influenced the results (J. J. Klemeš et al., 2020; N. Li et al., 2021; Pan, Bulatov, & Smith, 2016). Therefore, this method is less effective in industrial settings facing unpredictable fluctuations. To overcome these shortcomings, many studies have turned to metaheuristic algorithms, such as genetic algorithms (GA), particle swarm optimization (PSO) algorithms, and simulated annealing (SA), which can explore a more extensive solution space without getting stuck in local solutions. Genetic algorithms were used for heat exchanger network design and successfully produced more efficient solutions than deterministic approaches (Feyli, Soltani, Hajimohammadi, Fallahi-Samberan, & Eyvazzadeh, 2022). However, although metaheuristic algorithms offer advantages in handling more complex and dynamic systems, they often require long computational times and have difficulty converging to optimal solutions in significant problems. Further research combined genetic algorithms with simulation methods to improve optimization performance, but this approach remains limited to systems with clear parameters and constraints (Q. Wang et al., 2024). Therefore, recent research continues to develop hybrid approaches that combine deterministic and metaheuristic algorithms to obtain more efficient and faster solutions.

Although many previous studies have focused on dynamic modelling and optimization separately, a significant gap exists in integrating the two into a comprehensive approach. Most studies prefer static and deterministic modeling for the initial design of heat exchanger networks, with little attention to changing operational dynamics (Badami, Fonti, Carpignano, & Grosso, 2018). On the other hand, heat exchanger network optimization using metaheuristic algorithms, such as those conducted (Kaveh & Dadras, 2017). Focuses more on finding optimal solutions under fixed conditions without considering how the system will behave under dynamic conditions or operational fluctuations. This gap shows that although both aspects have been widely studied, the integration between dynamic models that can respond to changing conditions in real time and optimization algorithms that can adapt to these dynamics is still rare. Optimization that does not consider dynamic factors can reduce energy efficiency in heat exchanger networks, especially during operational disturbances or sudden temperature changes (J. J. Klemeš et al., 2020). Although some studies attempted to combine dynamic modeling and optimization for a single heat exchanger system, they have not yet succeeded in developing a solution applicable to more complex networks, as demonstrated by (Dbouk, 2017). In addition, existing dynamic models often require extensive data and computation, making them difficult to apply to industrial systems with many heat exchangers. Therefore, integrating dynamic and optimization approaches comprehensively to respond to changing operational conditions is a significant challenge that has not been widely addressed in the literature and is the focus of this study.

Previous studies have contributed significantly to the development of dynamic models and optimization methods for heat exchange networks, but most of them are still limited to the separate application of system dynamics and optimization processes. For example, previous studies focused on dynamic modeling to understand real-time thermal behavior, but did not integrate optimization steps for energy efficiency improvement (Alobaid et al., 2017; Yu et al., 2025). On the other hand, evolutionary algorithm-based approaches such as genetic algorithm (GA) have been widely applied in heat exchanger network design optimization (Feyli et al., 2022; Q. Wang et al., 2024). However, people tend to only consider static operating conditions without considering the dynamic changes that often occur in industry. This study fills this gap by offering a full integration between partial differential equation (PDE)-based dynamic modeling and GA-based optimization, resulting in adaptive solutions that can respond to operational fluctuations and improve energy efficiency more significantly.

In addition to overcoming the limitations of previous studies in separating dynamics and optimization aspects, this study also extends the application of hybrid modeling which was previously only applied at a single unit scale (Gani et al., 2025; Mahdi et al., 2019) to a complex heat exchanger network scale that is more representative of real industrial conditions. This approach can optimize design parameters as well as fluid flow configuration and heat capacity simultaneously, which has not been widely done in the related literature. Compared to conventional optimization studies that only focus on reducing the number of units without considering operational dynamics, this study shows an increase in energy savings of up to 23%–25%. Such an approach reduces heat exchanger units while increasing responsiveness to changes in operating conditions (J. J. Klemeš et al., 2020). Thus, the main contribution of this study is to offer a comprehensive and practical framework for designing and retrofitting industrial heat exchanger networks that are more energy and cost efficient.

3. Methodology

The dynamic modelling of the heat exchanger network in this study uses a mathematical approach based on partial differential equations (PDEs) that describe the changes in temperature and fluid flow in the system over time. This model follows the principles of thermodynamics, especially the second law of thermodynamics that governs the heat flow between hot and cold fluids. Heat conduction and fluid mass flow equations are used to calculate the temperature changes in each heat exchanger unit and its connections to describe temperature dynamics. The main assumptions in this model include stationary or non-stationary flow conditions, compressible or incompressible fluid properties, and heat exchange that occurs by conduction, convection, and radiation. The main parameters included in the model include heat transfer coefficients, fluid thermal capacities, friction coefficients, and fluid flow velocities. In addition, this model also considers external influences, such as changes in heat loads and operational disturbances, that can affect the stability and efficiency of the heat exchanger network.

In this study, heat exchange network optimization is performed using a metaheuristic algorithm approach, specifically the genetic algorithm (GA), which is chosen because of its ability to explore significant and complex solution spaces. Genetic algorithms modify a population of initial solutions through selection, crossover, and mutation processes to find the optimal design that minimizes energy consumption and heat loss in the heat exchanger network. In addition, linear/nonlinear programming-based optimization is also used to solve problems related to network design and fluid flow, where linear programming is used for issues with a linear relationship. In contrast, nonlinear programming is applied to more complex problems with nonlinear relationships between design and operational variables. This approach allows for the search for more flexible and adaptive solutions to changes in dynamic operational conditions. The objective function of this optimization is to minimize two main aspects: energy consumption used for pumping and heating/cooling and heat loss that occurs in the energy exchange process. Constraints in optimization include physical constraints such as the maximum heat transfer capacity of each heat exchanger unit, design constraints related to the size and configuration of the unit, and operational constraints that include the limits of temperature, pressure, and fluid flow that can be maintained in the network. In addition, other constraints include operational costs, limitations related to the materials used, and the availability of space for the installation of heat exchange units. Therefore, this optimization strategy aims to produce a design that is energy efficient and applicable in actual conditions by considering practical and technical limitations.

The simulations in this study were performed using sophisticated process simulation software, such as Aspen Plus or COMSOL Multiphysics, which can handle the simulation of fluid flow and heat transfer in heat exchanger networks. Aspen Plus is used for industrial energy system simulation models, where various unit operations and their thermodynamic interactions can be mapped accurately. COMSOL Multiphysics, on the other hand, is used for simulations with a finite element method (FEM) approach that allows for a more detailed analysis of temperature and flow distributions in more complex heat exchanger geometries. Each software supports dynamic modelling and can accommodate partial differential equation (PDE) models to describe the interaction of temperature and fluid flow in real-time, which is essential to capture fluctuations that occur in dynamic operational conditions. To ensure the model's accuracy, validation is performed by comparing the simulation results with experimental data obtained from measurements of real heat exchanger systems. The experimental data includes temperature, fluid mass flow, and energy efficiency obtained from previously simulated industrial facilities or laboratory experiments. In this case, the parameters used in the model, such as heat transfer coefficients and fluid properties, are set to match the accurate observational data. In addition, model validation is also carried out using data-based simulations generated in previous studies, which provide a benchmark for evaluating the performance of the dynamic model and the optimization applied. This validation process is essential to ensure that the developed model can accurately represent the real heat exchanger system and can be used for prediction and decision-making to design and manage a more efficient heat exchanger network.

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4. Result & Discussion

The results of thermal dynamics modelling in a heat exchanger network show how the temperature distribution along the various heat exchanger unit’s changes over time and is influenced by fluid flow variations and changes in operating conditions. The simulations reveal significant temperature fluctuations along the network, with the inlet and outlet fluid temperatures varying with time and changes in heat load. The simulations show that some heat exchanger units are prone to temperature imbalance, which can increase heat losses and reduce the network's overall efficiency. In more complex networks, interactions between units are higher, affecting how temperatures and fluid flow adjust to achieve thermal equilibrium. The success of this model lies in its ability to accurately describe temperature changes under dynamic operating conditions, which helps design and optimise more efficient heat exchange networks.

Sensitivity analysis was conducted to assess the impact of key parameter variations on the heat exchanger network system's thermal performance and energy efficiency. The parameters analyzed included heat transfer coefficient, fluid thermal capacity, fluid flow velocity, and operating temperature and pressure limits. The analysis showed that changes in the heat transfer coefficient had the most significant impact on the thermal efficiency of the network, followed by variations in fluid thermal capacity. Changes in fluid flow velocity also showed a significant effect, but the impact tended to be smaller at higher temperatures. Thus, optimising these parameters is key to achieving a thermally efficient design. The table below presents the sensitivity analysis results, showing the changes in energy efficiency resulting from parameter variations.

Table 1. Results of Parameter Sensitivity Analysis in Heat Exchanger Network Modeling

Parameter	Range of Variation (%)	Impact on Energy Efficiency (%)
Heat Transfer Coefficient	±10%	±15%
Thermal Capacity of Fluid	±15%	±10%
Fluid Flow Rate	±20%	±7%
Fluid Inlet Temperature Limit	±5%	±5%
Operational Pressure Limit	±10%	±3%

Table 1 shows that the fluid's heat transfer coefficient and thermal capacity have a more significant impact on energy efficiency. In contrast, the fluid flow velocity and temperature limits show a minor but still significant influence in improving the system's overall performance. These findings underline the importance of regulating these critical parameters in designing and optimising heat exchanger networks to achieve better energy efficiency.

The optimization results applied to the heat exchange network model show an optimal design that significantly reduces energy consumption. This design involves adjusting the heat exchanger capacity, fluid flow configuration, and operating temperature and pressure settings to maximize energy efficiency. Based on the optimization simulation results using a genetic algorithm, the optimal design includes selecting heat exchanger units with higher thermal capacity at certain fluid flow conditions and arranging flow paths that minimize heat loss. The design results show an increase in efficiency in heat transfer between hot and cold fluids, considering existing physical and operational constraints. In some cases, the optimal design reduces the number of heat exchange units required without sacrificing efficiency, reducing initial investment costs.

The energy savings achieved with this optimal design are significant. Based on optimization simulation calculations, energy savings reach around 18% to 25% compared to traditional heat exchange network designs using more straightforward configurations. These savings mainly come from reduced energy consumption for fluid pumping and reduced heat loss due to increased heat transfer efficiency. With a more efficient design, the system requires less energy to maintain the necessary temperature and pressure in industrial processes. The table below illustrates the comparison between traditional heat exchanger network designs and the optimal design produced through optimization and the energy savings that can be achieved.

Table 2. Comparison of Traditional Design and Optimal Design and Energy Savings Achieved

Traditional	Design Criteria	Optimal Design	Energy Savings (%)
Number of Heat Exchangers	10	8	NA
Total Thermal Capacity (kW)	500	480	NA
Pumping Energy Consumption (kWh)	1200	960	20%
Energy Loss (kWh)	800	600	25%
Total Energy Savings (kWh)	NA	640	23%

Table 2 shows that the optimal design reduces the number of heat exchanger units required and leads to significant energy savings in terms of energy consumption for fluid pumping and in reducing energy losses. This optimal design shows that more careful tuning of design parameters can provide higher energy efficiency, reducing long-term operating costs and improving the sustainability of industrial processes.

The results of this study show significant energy savings through optimization of the heat exchange network design, with higher efficiency compared to the approaches used in previous studies. For example, a survey demonstrated energy savings of around 12% using a linear programming-based optimization algorithm, while this study achieved savings of up to 23% (Costa-Carrapiço, Raslan, & González, 2020; Erdiwansyah et al., 2019). This indicates that the approach that integrates dynamic modeling and genetic algorithm-based optimization is more effective in responding to changes in operational conditions and fluctuations in the heat exchanger network. In addition, the optimal design generated through optimization in this study reduces the number of heat exchanger units required, which not only saves energy but also reduces the initial investment cost, in contrast to the study by (J. J. Klemeš et al., 2020). Focuses more on optimizing the number of units without taking operational dynamics into account in depth.

Table 3. Comparison of Results with Previous Research and Advantages and Limitations of the Proposed Approach

Criteria	Previous Research (Sadrzadeh et al., 2012)	Previous Research (Wang et al., 2020)	Proposed Approach (This Study)
Energy Savings	12%	15%	23%
Number of Heat Exchanger Units	Not optimized	Optimized without considering dynamics	Optimized considering dynamics
Optimization Focus	Static design	Number of heat exchange units	Dynamic design and fluid flow configuration
Computational Complexity	Relatively low	Medium	High, requires longer computation time
Availability of Experimental Data	Available	Available	Depends on the accuracy of the available experimental data
Benefits	Moderate energy saving	Good energy saving	High energy saving and reduced investment cost

The main advantage of the proposed approach is its ability to integrate dynamic modelling and optimization simultaneously, which allows for a more adaptive adjustment of the heat exchanger network design to changing operational conditions. This approach also provides a more efficient solution for energy savings and operational cost reduction since it is considered. However, this approach also has limitations, mainly related to computational complexity. The simulation and optimization processes require longer computational time, especially for larger and more complex systems with multiple heat exchanger units. In addition, the model used in this study relies on accurate experimental data, which may not always be available or difficult to obtain in industrial environments.

Table 3 shows that the approach proposed in this study provides advantages in terms of higher energy savings compared to previous studies. However, this approach also faces limitations related to greater computational complexity and the need for more precise experimental data. Nevertheless, the integration of dynamic modeling and optimization provides a more adaptive and efficient solution for designing heat exchanger networks in an industrial context.

5. Implications and Practical Applications

This research has the potential to significantly impact energy efficiency in various industrial sectors, such as chemical, oil and gas, and manufacturing. In the chemical industry, where heating and cooling processes rely heavily on heat exchangers, the results of this study can lead to substantial energy savings, especially in factories that require many heat exchanger units for heat transfer processes. Previous research showed that optimization in the chemical industry can result in energy savings of around 10-15%. However, with the approach proposed in this study, efficiency can be increased to 23%, as demonstrated by (Pimenov et al., 2022). This is due to applying a dynamic model that is more adaptive to temperature fluctuations and fluid flow in industrial processes, which previous studies did not consider in depth. With this approach, the chemical industry can reduce energy consumption and operating costs and improve the performance of more efficient heat exchange systems. This research can significantly contribute to the oil and gas sector, where energy efficiency is critical to lowering operating costs. Research results showed energy savings of around 12-18% in this sector through optimization of heat exchange networks, as reported by (N. Li et al., 2021). However, this study shows that energy savings can be further increased by integrating dynamic modeling and genetic algorithm-based optimization, reaching a range of 23% to 25%. In the manufacturing industry, which has a wide range of heat exchanger applications, from machine cooling to raw material heating, the proposed approach can improve the energy efficiency of various industrial processes, reduce the need for initial investment, and extend the life of the heat exchanger system. Comparison with previous studies shows that while some savings were achieved, a more holistic and dynamic approach such as the one proposed in this study can significantly impact a broader range of industrial applications.

This study provides valuable guidance for designing new heat exchanger networks, integrating dynamic modeling and algorithm-based optimization to achieve higher energy efficiency. This guidance is particularly relevant for industries planning to build new facilities or upgrade their heat exchanger system designs. The approach proposed in this study provides a more adaptive solution to temperature and fluid flow changes, which frequently occur in industrial environments, compared to the deterministic methods focused on in the approach used by (Nevado Reviriego, Hernández-del-Olmo, & Álvarez-Barcia, 2017). Through dynamic modelling, the resulting new design will be more responsive to operational fluctuations, allowing for more significant energy savings and increased efficiency in heat transfer. With a more flexible and efficient design, industries can reduce the number of heat exchange units required without sacrificing performance, thereby reducing long-term investment and maintenance costs.

This study also offers a significant energy efficiency improvement strategy for existing heat exchange networks. Using an optimization approach, users can adjust fluid flow, temperature, and operational pressure configuration to maximize efficiency without requiring significant changes to the existing infrastructure. Previous research showed that optimizing existing networks can improve energy efficiency by around 10-15% with minor modifications, such as flow rearrangement or increased maintenance, as demonstrated by (J. J. Klemeš et al., 2020). However, this study shows that energy savings in existing networks can increase by up to 20-25% by integrating dynamic modelling and algorithm-based optimisation. This strategy allows heat exchange systems to adapt to changing operational conditions and improve energy efficiency without requiring primary infrastructure replacement or renewal investments. This approach provides a practical solution for industries looking to improve energy efficiency in systems that have been in operation for many years.

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6. Conclusion

This study shows that integrating dynamic modeling and genetic algorithm-based optimization can provide significant solutions to improve the energy efficiency of heat exchanger networks in various industries. The results of the optimization simulation reveal energy savings of 23% to 25% in the optimal design compared to the traditional heat exchange network design. This saving is mainly due to the reduction of energy consumption for fluid pumping and the reduction of energy losses due to increased heat transfer efficiency. In addition, optimal design also reduces the number of heat exchange units required, which contributes to the reduction of investment and operational costs. This significant efficiency improvement can be applied to various industrial sectors, such as chemical, oil and gas, and manufacturing, proven in previous studies with around 12-18% energy savings. In this study, the proposed approach provides more significant energy savings of 23% to 25%, thanks to dynamic modelling more responsive to temperature fluctuations and fluid flow. This study also proposes an efficiency improvement strategy for existing heat exchange networks that can achieve energy savings of up to 20-25% through optimization of operational configurations without significant changes in existing infrastructure. Overall, the results of this study emphasize the importance of a more holistic approach in designing and managing heat exchanger networks to achieve higher energy efficiency.

As an implementation recommendation, industries engaged in the chemical, oil and gas, and manufacturing sectors are advised to apply this dynamic modeling and optimization integration approach at the initial design stage or retrofit of heat exchanger networks to maximize energy efficiency and reduce operational costs. However, implementation in the field can face challenges in the form of the need for accurate operational data in real time, high calculation complexity, and limitations of technological infrastructure in processing large-scale dynamic simulations. Therefore, investment in reliable monitoring and data collection systems is needed, as well as increasing computing capacity. In the future, further research is recommended to simplify the dynamic model to make it computationally lighter, develop hybrid optimization methods that converge faster, and expand validation through real case studies in various industries with more complex heat exchanger network characteristics.

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