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Scheduling and heat integration of multi-product plant based on genetic algorithm

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ABSTRACT

The research on scheduling and heat integration of batch process plays an important role in reducing energy consumption, improving production efficiency and enhancing the competitiveness of industries. The complexity and difficulty of the model solving are increased due to the comprehensive consideration of both scheduling and heat integration. In this paper, the mixed integer nonlinear programming (MINLP) mathematical model of multi-product plant heat integration optimization with the goal of energy-saving annual profit (EAP) is established. The simultaneous optimization and sequential optimization are carried out respectively by bi-level programming (BP) based on the genetic algorithm (GA), and the calculation results are compared. EAP better captures the trade-off relationship between scheduling schemes, energy-saving profits, and equipment costs. The bi-level programming approach based on GA categorizes variables into integer and real types, enabling structural optimization and parameter optimization of the heat exchanger network. This, in turn, enhances solution efficiency and overcomes the limitations of conventional optimization algorithms in terms of solution speed and quality. Two examples show that the EAP of indirect heat integration considering the storage tank are 21% and 2% higher than that of the direct heat integration, and EAP of the simultaneous optimization are 26% and 6% higher than that of the sequential optimization. The example demonstrates that the model and algorithm are applicable to batch multi-product plants, such as those in the chemical, pharmaceutical, and food industries, and possess strong practicality and innovation.

1. Introduction

Batch chemical process [1] is famous for its low investment, rapid start-up, strong flexibility, easy expansion and transformation. It is especially suitable for products with small production volume, high output value, wide variety, rapid market changes and fast listing speed, and has a significant competitive advantage [2] in the fields of specialty chemicals, bio-chemicals, and non-mass production customized to customer orders. It is of great theoretical and practical significance to study the energy integration in batch process system [3] from the perspective of overall system optimization [4] for saving investment, reducing energy consumption, reducing environmental pollution, and improving the design and operation of batch chemical process [5].

According to the difference of the content and depths of the research on the optimization of energy for multi-product plant, the problem concerning heat integration of batch multi-product plant falls into two categories: heat integration model under certain scheduling and heat integration model under uncertain scheduling. The study of heat integration under batch process scheduling commenced in the 1980s. Linnhoff *et al.* [6] utilized the pinch technology and the problem table method to solve the ' bottleneck ' problem in the process system. The strategy of solving the ' bottleneck ' provides a framework of thinking for the heat integration in batch processes. Clayton [7] proposed the Time Average Method (TAM) to assess the heat integration potential of batch processes. However, since the model does not account for the specific timing of stream matching, it can only give an ideal stream matching, and the scheme may not meet the expectations. Crump [8] proposed the time slice method (TSM) which considering the discrete nature of the flow in batch processes. This model can solve the direct heat integration and can be combined with the capacity of equipment, yield, and energy consumption to optimize

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the problem. The problem can be optimized, but the model cannot achieve the stream matching function between different time periods. Based on the TSM, Kemp *et al.* [9–11] proposed a time-dependent heat cascade analysis (TDHCA), which can identify opportunities of heat storage directly and obtain a heat integration scheme under certain scheduling. However, this method lacks specific information on heat storage or release in the application process. Foo *et al.* [12,13] extended the minimum units targeting and network evolution techniques which were developed from batch mass exchange network into batch heat exchange network. A novel targeting technique is introduced for determining minimal resource and waste targets in batch process integration problems. However, this method can only solve the heat integration situation under certain scheduling, without considering the extra heat transfer temperature difference of indirect heat exchange and may fall into the local optimal solution. Chaturvedi *et al.* [14,15] proposed a rigorous algorithm to determine the minimum amount of utilities in batch scheduling, considering the extra heat transfer temperature difference of indirect heat transfer and the influence of product streams stored. However, this method neglects the temperature changer of the intermediate heat exchange medium, and may fall into local optimum or infeasible solution. Shahane *et al.* [16] proposed a direct heat transfer method based on virtual temperature, which considers both direct and indirect heat exchange. However, in designing an integrated heat exchange network, their objective is relatively singular, leading to a more complex heat exchange network and higher annual comprehensive costs. Mummana *et al.* [17–19] proposed an innovative, unified mathematical approach employing a three-index, unit-specific, event-driven formulation to address the cyclic scheduling of multi-purpose plants. When cyclic scheduling is not a factor, this comprehensive framework simplifies significantly. By incorporating the concept of active tasks, the extension of tasks into subsequent cycles is seamlessly integrated with short-term scheduling constraints. But the solution model is more complex because it is solved in stages and difficult to obtain a global optimal solution.

The problem of heat integration under uncertain batch process scheduling involves two aspects: scheduling and heat integration. Therefore, besides optimizing heat integration under specific scheduling conditions, it is essential to consider the interaction between batch process scheduling and heat integration through collaborative optimization. The heat integration model under batch process scheduling uncertainty is addressed through two methods: sequential optimization and simultaneous optimization. The sequential optimization approach tackles the heat integration problem in batch chemical process scheduling by splitting it into two sub-problems: The scheduling optimization of batch chemical process can obtain one or more scheduling schemes, followed by heat integration optimization to design a detailed heat integration scheme under each scheduling. Vaselenak *et al.* [20] employed heuristic method and mixed integer programming to determine the scheduling information of batch process, followed by analyzing the possibility of heat recovery under different heat transfer modes. Bozan *et al.* [21] optimized the heat exchanger network using a two-step approach. Firstly, the distribution of heat exchanger was obtained through production scheduling information, and then the MINLP model was established to optimize the heat exchanger network system. Halim *et al.* [22] solved the problem by the continuous time model in three sequential steps, (1) solving the conventional scheduling problem to optimize the system scheduling for economic objectives (*e.g.*, minimum completion time, maximum profit), (2) adjusting scheduling information using cutting plane method to generate candidate schedules, and (3) performing heat integration optimization using TAM or TSM models for each schedule to identify the optimal scheme. Simultaneous optimization integrates scheduling and heat integration in batch chemical processes, balancing production efficiency and energy consumption to achieve an optimal solution. Papageorgiou *et al.* [23] used discrete-time representation and state-task networks for this purpose. Lee and Reklaitis [24] developed a simplified model for single-stream matching in single-product multi-cycle operations without heat storage. Tokos and Pintarič [25] improved this model by focusing on utility reduction, enabling economic trade-offs between utility savings and heat exchanger costs. However, these single-stream matching models may miss global optima due to limited rematching opportunities. Romero *et al.* [26] employed a superstructure to represent scheduling and heat exchanger networks, using combination algorithms to solve one-to-one stream matching and reduce utilities by extending completion times. Castro *et al.* [27] proposed a general MILP model for simultaneous optimization but ignored the role of heat storage tanks in stream heat transfer. In summary, the sequential optimization strategy utilizes a hierarchical problem decomposition methodology, wherein the initial candidate scheduling scheme is derived through either heuristic algorithms or single-objective economic criteria coupled with single-stream matching protocols. This is subsequently refined *via* localized optimization techniques, including but not limited to completion time adjustments and heat storage integration. Nevertheless, this paradigm fails to account for the cascading effects of subsequent heat exchange optimization on the global objective function. While computationally expedient, this approach demonstrates a pronounced propensity for local optima convergence. Conversely, the simultaneous optimization paradigm, though capable of generating globally optimal solutions, incurs substantial computational overhead and exhibits significantly heightened model complexity, particularly in large-scale industrial applications.

At the same time, most of the above models are solved by GAMS [28], but for the MINLP problem, as the scale of the problem increases, there is a combinatorial explosion, making it very difficult for GAMS to solve. In addition, the performance and availability of the solver may become limited as the scale and complexity of the problem increase. Compared with the limitations of deterministic algorithms (such as branch and bound, outer approximation) in solving structured MINLP problems within GAMS, stochastic algorithms (*e.g.* SA, GA, PSO) exhibit more advantages in terms of global search ability, parallelism potential, and robustness. They are especially suitable for scheduling uncertain heat integration models. Compared with other optimization techniques, such as Simulated Annealing (SA), Genetic Algorithm (GA) offers several core advantages [29]. It enhances population diversity through crossover and mutation, effectively avoiding local optima [30]. Unlike SA and other techniques, which relies on random disturbances of a single solution and is more sensitive to the initial solution's quality, GA's population-based search supports parallel computing, making it suitable for large-scale complex systems like chemical batch process scheduling and heat integration [31]. Furthermore, GA is easily extensible to multi-objective optimization (*e.g.*, economic and environmental factors), particularly suitable for chemical batch process [32]. Given its global robustness, parallel scalability, and multi-objective optimization capabilities, GA has become the preferred choice for the simultaneous optimization of batch process scheduling and heat integration [33]. Unlike existing research, which primarily focuses on batch process scheduling and direct heat integration in multi-product plants, this study addresses a key research gap by introducing and systematically comparing direct and indirect heat integration methods. This provides a more comprehensive framework for heat integration optimization in batch chemical processes. Moreover, in contrast to existing solution strategies that rely heavily on GAMS solvers, this study fills another crucial research gap by introducing a bi-level programming method based on a genetic algorithm. It adopts a simultaneous optimization strategy that integrates scheduling and heat integration as a whole, thus offering a novel approach for optimizing batch chemical process scheduling and heat integration solutions.

In this paper, a MINLP mathematical model is established for heat integration optimization in a multi-product plant, with the primary objective of maximizing EAP. This model, based on the GA and the TDHCA method, comprehensively considers scheduling task time, heat integration energy, utility cost, and equipment cost. To tackle the complexity of the heat integration model in a multi-product plant, the problem is decomposed into two optimization levels: scheduling and heat integration. At the scheduling optimization level, integer optimization is employed to determine the optimal processing order of products. At the heat integration optimization level, the TDHCA method is utilized to determine the most efficient matching scheme between direct and indirect heat integration. The EAP serves as the fitness function to evaluate the quality of each solution, guiding the search towards the optimal MINLP solution. A novel aspect of this study is the application of GA, which is used to solve the model through both sequential and simultaneous optimization approaches. This dual approach yields corresponding scheduling and heat integration optimization schemes, allowing for a comprehensive comparison and analysis of the results. To demonstrate the effectiveness of the proposed method, two practical examples are provided, showcasing the significant improvements in EAP achieved through the optimization process.

2. Problem Description

The energy saving in multi-product plant mainly includes two aspects: scheduling and heat integration. The production of each product in the multi-product plant needs to be processed on the equipment, and each stream only exists within a specific time frame. Therefore, the start and end time of each stream must be considered when performing pinch analysis. In this paper, the processing task time of each product on different equipment, the initial and target temperature of each stream and the heat load are all known. Based on the known data, the total scheduling time and the minimum utility of the multi-product plant are calculated. Ultimately, the objective function is the EAP after sequential optimization and simultaneous optimization of multi-product plant scheduling and heat integration. The scheduling sequence and equipment operation Gantt chart are determined, and the heat exchange network diagram of multi-product plant is drawn.

3. Theoretical Modeling

3.1. Determination of optimal scheduling sequence

In order to ensure that all products undergo one processing task on all equipment as the production goal, a mathematical model is constructed for the scheduling of the production process. The type of intermediate storage tank [34] in multi-product process is subjected to the process of the products and the stability of intermediate products, and the unlimited intermediate storage (UIS) tank is used as the example. Considering that each device can only process one product in the same time period, and each product can only enter one device for processing in the same time period. The constraint conditions (1) and (2) are given: the equation $B(i,k)=1$ means that the product k is processed on the equipment i.

$$\sum_{i=1}^{N} B(i,k)=1 \tag{1}$$

$$\sum_{k=1}^{M} B(i,k)=1 \tag{2}$$

Constraint (3) requires that the time difference between product i and product $i-1$ leaving the same processing equipment j is not less than the processing time of product i on the equipment j. Constraint (4) requires that the time difference between product i leaving the processing equipment j and $j-1$ is not less than its processing time on the unit j. $F(i,j)$ is the completion time point of product i on the device j of the production process, and $t(k,j)$ is the processing time of product k on the device j of the production process.

$$\left[F(i,j)-F(i-1,j)-\sum_{i=1}^{N} t(k,j)B(i,k)\right]\geq 0 \tag{3}$$

$$\left[F(i,j)-F(i,j-1)-\sum_{k=1}^{M} t(k,j)B(i,k)\right]\geq 0 \tag{4}$$

The completion time of the process greatly impacts the production efficiency of the system in the production process. Therefore, when the production sequence of various products is known, the completion time of the each process must satisfy certain constraints: the equation $F(i,j)=0$ means that the product i is not processed on the device j.

$$F(i,j)=\max[F(i-1,j),F(i,j-1)]+t(k,j) \quad i=1,2,\cdots,N; j=1,2,\cdots,M \tag{5}$$

$$F(i,j)=0 \qquad i=0 \text{ or } j=0 \tag{6}$$

3.2. Heat integration under determined scheduling sequence

Based on the time-temperature cascade method, Foo *et al.* [12,13] established a mathematical model utilizing thermal cascade analysis to determine the minimum utility consumption in the multi-product plant process. The model calculates the minimum utility consumption of each time period by considering the heat sink and heat source within each time period, and sums them to obtain the overall minimum utility consumption of the process. It mainly includes time period determination and temperature determination. Firstly, according to the scheduling sequence, the starting time point t_{is} and the completion time point t_{ie} of each product are determined and put into a set, and then all the time points $\{t_{1s}, t_{1e}, \cdots, t_{ns}, t_{ne}\}$ in the set are sorted in ascending order. The time period between two adjacent time points defines the required time period, and the number of time periods is $2n-1$. The virtual temperature method is used to determine the temperature interval. The virtual temperature is determined by the minimum heat transfer temperature difference ΔT_{min} and subjected to the temperature constraints (7) and (8). T_1 is the inlet temperature of the hot stream, T_2 is the outlet temperature of the hot stream, t_1 is the inlet temperature of the cold stream, and t_2 is the outlet temperature of the cold stream.

$$T_1-\frac{\Delta T_{min}}{2}\geq t_2+\frac{\Delta T_{min}}{2} \tag{7}$$

$$T_2 - \frac{\Delta T_{\min}}{2} \geq t_1 + \frac{\Delta T_{\min}}{2} \tag{8}$$

In the thermal cascade model of each time period, ranging from the highest temperature to the lowest temperature, it is divided into n temperature intervals. The virtual temperature of each temperature interval is determined by the movement of the cold and hot streams at the initial and target temperatures. The energy balance is established for each temperature interval, which includes the heat sink and heat source in a certain time period, as well as the heat storage input in the previous interval and the heat storage output in the next time period. In the time period t, the heat sink $QC_{t,k}$ and heat source $QH_{t,k}$ of the temperature interval k are determined by the heat capacity flow rate of the stream and the temperature difference between the upper and lower limits of the temperature interval: $QC_{t,k}$ is the heat sink of temperature interval k in time period t, $QH_{t,k}$ is the heat source of temperature interval k in time period t, $CP_{i,t,k}$ is the heat capacity flow rate of temperature interval k in time period t of cold stream i, $CP_{j,t,k}$ is the heat capacity flow rate of temperature interval k in time period t of hot stream j, q_k is the initial temperature or target temperature of temperature interval k. Δt is the duration.

$$QC_{t,k} = \sum_i CP_{i,t,k}(q_k - q_{k+1})\Delta t \qquad k \in K, t \in T \tag{9}$$

$$QH_{t,k} = \sum_j CP_{j,t,k}(q_k - q_{k+1})\Delta t \qquad k \in K, t \in T \tag{10}$$

For the time period t, the heat storage $(ST_{t-1,t})_k$ from the previous time period is used as an additional heat source, which is added to the heat source $QH_{t,k}$ of the time period. The heat storage $(ST_{t,t+1})_k$ from the next time period is used as an additional heat sink, which is added to the heat sink $QC_{t,k}$ of the time period. The residual heat $\delta_{k,t}$ of the temperature interval k is obtained by adding the residual heat $\delta_{k-1,t}$ of the previous temperature interval to the net heat and net heat storage of the temperature interval: $\delta_{k,t}$ is the residual heat between the time period t and the temperature interval k, and $(ST_{t,t+1})_k$ is the heat storage from the temperature interval k time period t to the time period t+1.

$$\delta_{k-1,t} + \left(QH_t + ST_{t-1,t}\right)_k = \delta_{k,t} + \left(QC_t + ST_{t,t+1}\right)_k \qquad k \in K, t \in T \tag{11}$$

$$\delta_{k,t} \geq 0 \qquad k \in K, t \in T \tag{12}$$

$$\left(ST_{t,t+1}\right)_k \geq 0 \qquad k \in K, t \in T \tag{13}$$

If there is no heat storage tank, Eq. (12) becomes Eq. (14):

$$\delta_{k-1,t} + (QH_t)_k = \delta_{k,t} + (QC_t)_k \qquad k \in K, t \in T \tag{14}$$

Eq. (15) defines the cumulative heat storage $CST_{t,k}$. The heat storage STG_k of the temperature interval k is determined by the maximum value of the cumulative heat storage in each time period. For example, Eq. (16), the heat storage of each temperature interval should also be non-negative:

$$\left(CST_t - ST_{t-1,t} + ST_{t,t+1}\right)_k = (CST_{t+1})_k \qquad k \in K, t \in T \tag{15}$$

$$STG_k \geq (CST_{t+1})_k \qquad k \in K, t \in T \tag{16}$$

$$STG_k \geq 0 \qquad k \in K, t \in T \tag{17}$$

The first layer objective function is the minimum cumulative amount of hot utility FH_t in each time period:

$$\min \sum_t FH_t \qquad t \in T \tag{18}$$

When addressing the multi-product process scheduling and heat integration problem, it is necessary to consider not only the profit of the process, but also the scheduling time and equipment cost. Therefore, the second layer of our approach selects the energy-saving annual profit (EAP) as the optimization objective: ΔT_{m} is the logarithmic mean temperature difference (LMTD), °C; A_{e} is the area of heat exchanger, m^2; Q_{e} is the heat transfer duty of the heat exchanger, MJ; K_{e} is the heat transfer coefficient, kW·(m^2·°C)$^{-1}$; C_{e} is the cost of heat exchanger [11], USD.

$$\Delta T_{\mathrm{m}} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln((T_1 - t_2)/(T_2 - t_1))} \tag{19}$$

$$A_{\mathrm{e}} = \frac{Q_{\mathrm{e}}}{K_{\mathrm{e}} \times \Delta T_{\mathrm{m}} \times \Delta t} \tag{20}$$

$$C_{\mathrm{e}} = 401 \times {A_{\mathrm{e}}}^{0.71} \tag{21}$$

M_{s} is the mass of heat transfer medium, kg; Q_{s} is the heat transfer duty of the tank, MJ; ΔT_{s} is the temperature difference between inlet and outlet of heat transfer medium, °C; C_{w} is the specific heat of the heat transfer medium, MJ·(kg·°C)$^{-1}$; V_{s} is the volume of heat storage tank, m^3; ρ_{s} is the density of the heat transfer medium, kg·m^{-3}, and C_{s} is the cost of the heat storage tank [11], USD.

$$M_{\mathrm{s}} = \frac{Q_{\mathrm{s}}}{\Delta T_{\mathrm{s}} \times C_{\mathrm{w}}} \tag{22}$$

$$V_{\mathrm{s}} = \frac{M_{\mathrm{s}}}{\rho_{\mathrm{s}}} \tag{23}$$

$$C_{\mathrm{s}} = 1504 \times {V_{\mathrm{s}}}^{0.71} \tag{24}$$

FH_t is the actual consumption of hot utilities for t time period, MJ; SH is the unit cost of hot utility, USD·GJ^{-1}; FC_t is the actual consumption of cold utilities in t time period, MJ; SC is the unit cost of cold utility project, USD·GJ^{-1}; FH_{s} is the total hot utility without heat integration, MJ; FC_{s} is the total cold utility without heat integration, MJ; P is the energy-saving annual profit, USD; E is the total cost of non-heat integrated utilities, USD; U_{a} is the total cost of heat integrated utilities, USD; C_{a} is the total cost of actual equipment, USD.

$$C_{\mathrm{a}} = C_{\mathrm{e}} + C_{\mathrm{s}} \tag{25}$$

$$U_{\mathrm{a}} = \sum_t FH_t \times SH + \sum_t FC_t \times SC \qquad t \in T \tag{26}$$

$$E = FH_{\mathrm{s}} \times SH + FC_{\mathrm{s}} \times SC \tag{27}$$

$$P = E - U_{\mathrm{a}} - C_{\mathrm{a}} \tag{28}$$

3.3. *The solution idea of sequential optimization and simultaneous optimization*

The solution idea of sequential optimization is shown in Fig. 1 (a). In the case of uncertain scheduling of multi-product plants, the optimal scheduling sequence of the first level objective is solved by using the initial population and genetic operation of

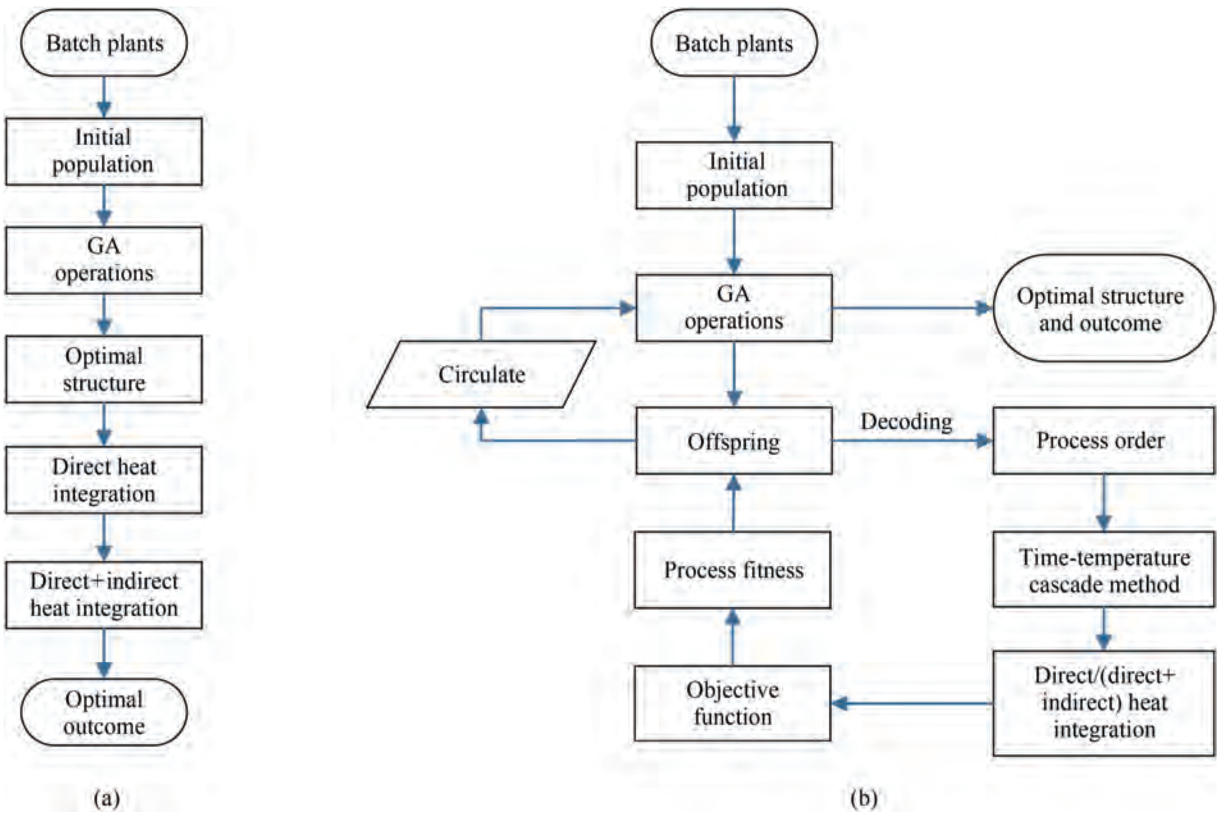

Fig. 1. Flowcharts of optimization: (a) sequential optimization, (b) simultaneous optimization.

GA. Under the optimal scheduling, direct heat integration matching and direct + indirect heat integration matching is performed in turn, and the heat integration scheme under the optimal scheduling of multi-product plants is obtained through the second-level objective function. The solution idea of simultaneous optimization is shown in Fig. 1(b). Considering the two uncertain BP problems of scheduling and heat integration of multi-product plants, the scheduling sequence is decoded by an initialization population and genetic operation, and the heat integration matching is carried out by TDHCA. The heat integration matching includes direct heat integration matching and direct + indirect heat integration matching respectively, and the fitness value of the objective function is obtained. According to the fitness, the offspring is iteratively optimized, and finally the system optimal solution of the scheduling and heat integration simultaneous optimization scheme of the comprehensive objective function is found.

Modifications are as follows: Simultaneous optimization and sequential optimization each have their own advantages and disadvantages in solving mixed integer nonlinear programming (MINLP) problems. Simultaneous optimization prioritizes the quality and physical coupling of solutions through global variable collaborative computing, such as in scheduling and heat integration joint modeling. It is especially suitable for small and medium-scale high-precision demand scenarios, like chemical process design. However, its high computational complexity, which requires distributed computing power support, and non-convex convergence issues limit its industrial-level applications. On the other hand, sequential optimization employs a problem decomposition strategy, such as scheduling before heat integration, to reduce the scale of single-step solutions, improve real-time performance, and enhance scalability. It is suitable for very large-scale systems or online optimization. However, this approach may sacrifice global optimality due to the decoupling of variable associations. The research indicates that the selection between these methods needs to balance the problem scale, resource constraints, and accuracy requirements. The former is more suitable for academic research or multi-objective joint optimization [35], while the latter is more suitable for plant-level real-time control [22].

4. Results and Discussion

4.1. Example 1

This example is adapted from Ref. [14]. Multi-product plants produce four different products. The processing of the products on two different equipment units in turn. The processing time for each product on each processing equipment unit is different, as shown in Table 1.

Sequential optimization step 1:

The storage form of the UIS tank is utilized to optimize the scheduling process of multi-product plants. The optimal product processing order is {3,2,4,1}. The minimum completion time of the process being 75 min. The production Gantt chart under the optimal production sequence is presented in Fig. 2.

Table 1
Processing time of product.

Product	Equipment 1/min	Equipment 2/min
1	7	5
2	25	20
3	15	15
4	20	10

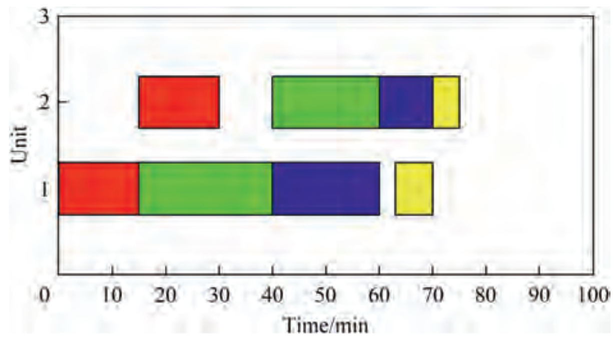

Fig. 2. Gantt chart of processing time of product.

Table 2
Costs for utilities.

Utility	Inlet temp./°C	Outlet temp./°C	Price/USD·GJ^{-1}
Cooling water	20	30	0.354
Hot steam	170	169	7.78

Table 3
Stream data for example 1.

Product	Inlet temp./°C	Outlet temp./°C	Heat transfer duty/MJ
1	20	135	2300
2	170	60	3300
3	80	140	2400
4	150	30	1800

According to the results, the method of utilizing UIS tank is more flexible in production time arrangement, and can obtain shorter completion time, but at the same time, it will increase the cost of equipment. After the production scheduling of the system is optimized, the heat integration analysis of multi-product plants is carried out. In this case, considering the minimum heat transfer temperature difference of 10 °C. According to the literature, the unit expenditure on utilities is presented in Table 2, and the flowing stock data of the process is detailed in Table 3.

Sequential optimization step 2:

The product processing sequence, product processing times, corresponding stock information and utility cost information of multi-product plants under optimal scheduling are known. The objective function is the minimum utility consumption and EAP of heat integration under the optimal scheduling of multi-product plants. The heat exchanger network structure (Figs. 3 and 4)

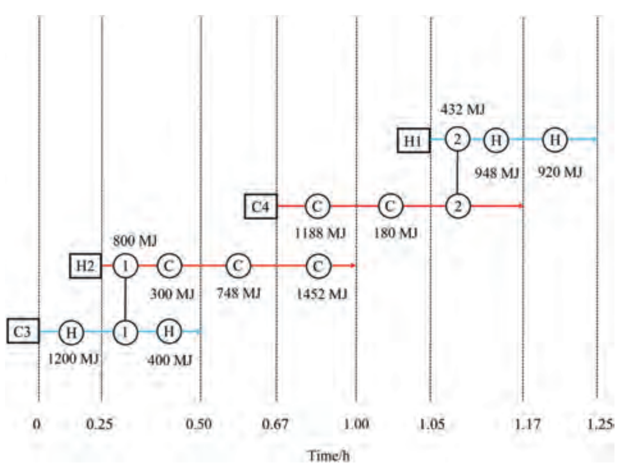

Fig. 3. Heat exchanger network of optimal scheduling direct heat integration.

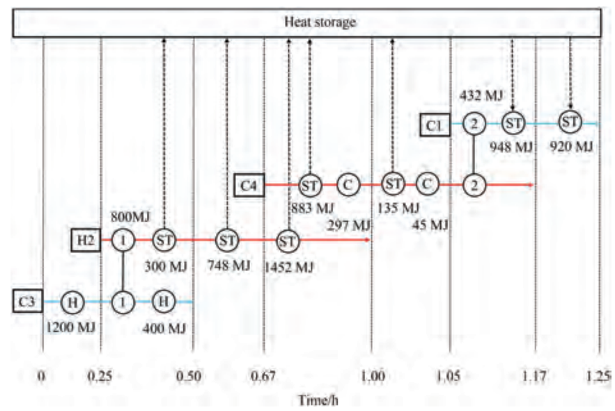

Fig. 4. Heat exchanger network of optimal scheduling of indirect heat integration.

include the start and end time of the streams, the heat exchange in the heat exchanger during each time period, the heat exchange in the storage tank and the utilization of utilities. Table 4 presents a comparative analysis of the results.

In this example, the cost of utilities required for each product processing in a multi-product plant is 38.37 USD. Under the optimal scheduling, the cumulative completion time of the system is 1.25 h. The heat integration optimization of the process is carried out within the production structure of the fixed optimal scheduling. The direct heat integration of one scheduling can save 1232 MJ of hot utility and cold utility. The percentages of saving hot utility and cold utility are 26.2% and 24.1% respectively. The total cost of one scheduling of saving utilities is 10.02 USD, but the EAP is increased by 31422 USD, resulting in an EAP ratio of 11.6%. The indirect heat integration of one scheduling can save 3100 MJ of hot utility and cold utility respectively. The percentages of saving hot utility and cold utility are 65.9% and 60.7% respectively. The total cost of one scheduling of saving utilities is 25.21 USD, but the EAP is increased by 92655 USD, resulting in an EAP ratio of 34.4%. Compared with direct heat integration, indirect heat integration saves 1868 MJ of hot utility and cold utility, thus increasing the EAP by 61233 USD and raising the EAP ratio by 22.8%.

Simultaneous optimization step 3:

After the simultaneous optimization of the circular solution strategy, the direct heat integration scheduling sequence is {3,2,1,4}. Fig. 5 illustrates the Gantt chart, and Fig. 6 depicts the simultaneous optimization direct heat integration heat exchange network.

After the simultaneous optimization of indirect heat integration, the multi-product plant scheduling processing sequence becomes {2,1,4,3}. Fig. 7 illustrates the Gantt chart, and Fig. 8 depicts the simultaneous optimization of indirect heat integration heat exchange network.

The initial conditions of the above examples are input into the multi-product plant process scheduling and heat integration circular simultaneous optimization process, resulting in the following Table 5.

In this example, after the process scheduling of multi-product plant and the simultaneous optimization of heat integration, the energy saving achieved through multi-product plant scheduling and direct integration simultaneous optimization is 1574 MJ higher than that of sequential optimization of hot utility and cold utility, respectively. The percentages of saving hot utility and cold utility are increased by 33.5% and 30.9%, respectively. The EAP is increased by 75699 USD, and the ratio of EAP improvement is 28.2%. Similarly, the energy saving from multi-product plant scheduling and indirect heat integration simultaneous

Table 4
Comparison of heat integration results.

	No integration	Direct heat integration	Direct + indirect heat integration
Hot utility/MJ	4700	3468	1600
Hot utility savings/MJ	0	1232	3100
Hot utility percentages of savings/%	0	26.2	65.9
Cold utility/MJ	5100	3868	2000
Cold utility savings/MJ	0	1232	3100
Cold utility percentages of savings/%	0	24.1	60.7
Total cost of utilities/USD	268906	198678	92197
Number of heat exchangers	4	6	7
Number of heat storage tanks	0	0	4
Total cost of equipment/USD	17762	38806	84054
Energy-saving annual profit/USD	0	31422	92655
Energy-saving annual profit ratio/%	0	11.6	34.4

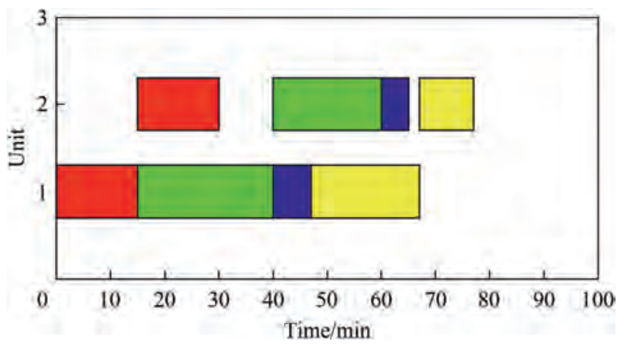

Fig. 5. Gantt chart of processing time of product.

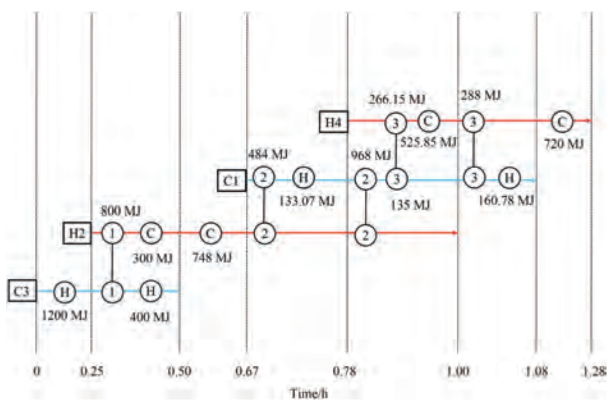

Fig. 6. Simultaneous optimization of heat exchanger network of direct heat integration.

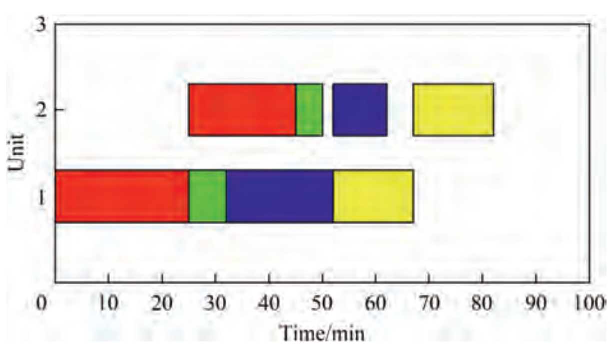

Fig. 7. Gantt chart of processing time of product.

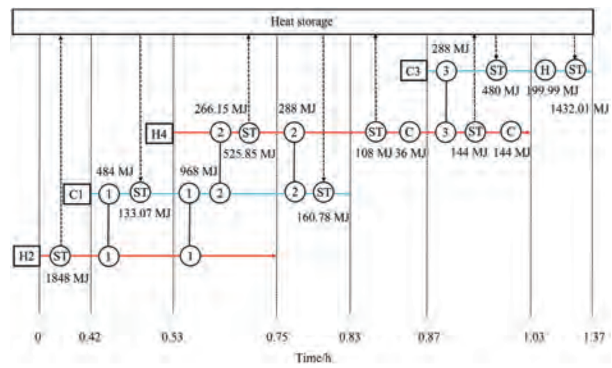

Fig. 8. Simultaneous optimization of heat exchanger network of indirect heat integration.

optimization is 1400 MJ higher than that of sequential optimization. The EAP is increased by 66934 USD, and the ratio of EAP improvement is 24.9%. Furthermore, when comparing multi-product plant scheduling and indirect heat integration simultaneous optimization to direct heat integration simultaneous optimization, the energy saving is 1694 MJ higher for hot utility and cold utility combined. The percentages of saving hot utility and cold utility are increased by 36% and 33.2%, respectively. The EAP is increased by 52468 USD, and the ratio of EAP improvement is 19.5%. In Tables 4 and 5, despite the increase in equipment cost, the utility cost savings exceed 50%. The EAP of indirect heat integration is 21% higher than that of direct heat integration, and the EAP of simultaneous optimization is 26% higher than that of sequential optimization. These results indicate that, although the optimal scheduling of simultaneous optimization may not be as good as that of sequential optimization in terms of pure scheduling efficiency, when scheduling and heat integration are considered at the same time, the increased profit outweighs the benefits of scheduling shortening time. Example 1 demonstrates the feasibility of the model.

4.2. Example 2

This example is adapted from Ref. [36]. Multi-product plants produce eight different products. The processing of the products on three different equipment units in turn. The processing time for each product on each processing equipment unit is different, as shown in Table 6.

Sequential optimization step 1:

The storage form of the UIS tank is utilized to optimize the scheduling process of multi-product plant. The optimal product processing order is {3,8,2,5,6,1,4,7}. The minimum completion

Table 5
Comparison of simultaneous optimization of heat integration results.

	No integration	Simultaneous optimization of direct heat integration	Simultaneous optimization of direct + indirect heat integration
Hot utility/MJ	4700	1894	200
Hot utility savings/MJ	0	2806	4500
Hot utility percentages of savings/%	0	59.7	95.7
Cold utility/MJ	5100	2294	600
Cold utility savings/MJ	0	2806	4500
Cold utility percentages of savings/%	0	55	88.2
Total cost of utilities/USD	268906	106402	11307
Number of heat exchangers	4	7	8
Number of heat storage tanks	0	0	4
Total cost of equipment/USD	17762	55383	98010
Energy-saving annual profit/USD	0	107121	159589
Energy-saving annual profit ratio/%	0	39.8	59.3

Table 6
Processing time of product.

Product	Equipment 1/min	Equipment 2/min	Equipment 3/min
1	61	2	56
2	42	32	42
3	1	31	71
4	46	98	42
5	11	14	20
6	35	89	75
7	66	8	25
8	25	46	44

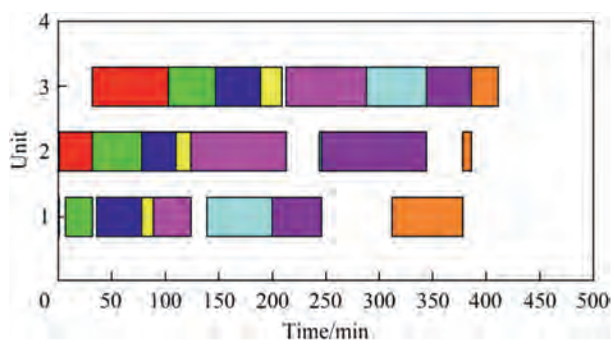

Fig. 9. Gantt chart of processing time of product.

time of the scheduling process being 411 min. The production Gantt chart under the optimal production sequence is presented in Fig. 9.

According to the results, the method of utilizing UIS tank is more flexible in production time arrangement, and can obtain shorter completion time, but at the same time, it will increase the cost of equipment. After the production scheduling of the system is optimized, the heat integration analysis of multi-product plants is carried out. In this case, considering the minimum heat transfer temperature difference of 10 °C. According to the literature, the unit expenditure on utilities is presented in Table 2, and the flowing stock data of the process is detailed in Table 7.

Table 7
Stream data for example 2.

Product	Entry temp./°C	Outlet temp./°C	Heat transfer/MJ
1	100	70	20000
2	70	100	11000
3	100	70	15000
4	50	70	9000
5	70	100	11000
6	50	70	5000
7	80	90	7000
8	60	130	24000

Sequential optimization step 2:

The product processing sequence, product processing times, corresponding stock information and utility cost information of multi-product plants under optimal scheduling are known. The objective function is the minimum utility consumption and EAP of heat integration under the optimal scheduling of multi-product plants. The heat exchanger network structure (Figs. 10 and 11) include the start and end time of the streams, the heat exchange in the heat exchanger during each time period, the heat exchange in the storage tank and the utilization of utilities. Table 8 presents a comparative analysis of the results.

In this example, the cost of utilities required for each product processing in a multi-product plant is 533.65 USD. Under the optimal scheduling, the cumulative completion time of the system is 6.85 h. The heat integration optimization of the process is carried out within the production structure of the fixed optimal scheduling. The direct heat integration of one scheduling can save 26489 MJ of hot utility and cold utility. The percentages of saving hot utility and cold utility are 39.5% and 75.6% respectively. The total cost of one scheduling of saving utilities is 215.46 USD, but the EAP is increased by 170954 USD, resulting in an EAP ratio of 25%. The indirect heat integration of one scheduling can save 34906 MJ of hot utility and cold utility respectively. The percentages of saving hot utility and cold utility are 52% and 99.7% respectively. The total cost of one scheduling of saving utilities is 283.92 USD, but the EAP is increased by 190312 USD, resulting in an EAP ratio of 27.8%. Compared with direct heat integration, indirect heat integration saves 8417 MJ of hot utility and cold utility, thus increasing the EAP by 19358 USD and raising the EAP ratio by 2.8%.

Simultaneous optimization step 3:

After the simultaneous optimization of the circular solution strategy, the direct heat integration scheduling sequence is {3,5,8,6,2,1,7,4}. Fig. 12 illustrates the Gantt chart, and Fig. 13 depicts the simultaneous optimization direct heat integration heat exchange network.

After the simultaneous optimization of indirect heat integration, the multi-product plant scheduling processing sequence becomes {3,5,6,8,7,1,2,4}. Fig. 14 illustrates the Gantt chart, and Fig. 15 depicts the simultaneous optimization of indirect heat integration heat exchange network.

The initial conditions of the above examples are input into the multi-product plant process scheduling and heat integration

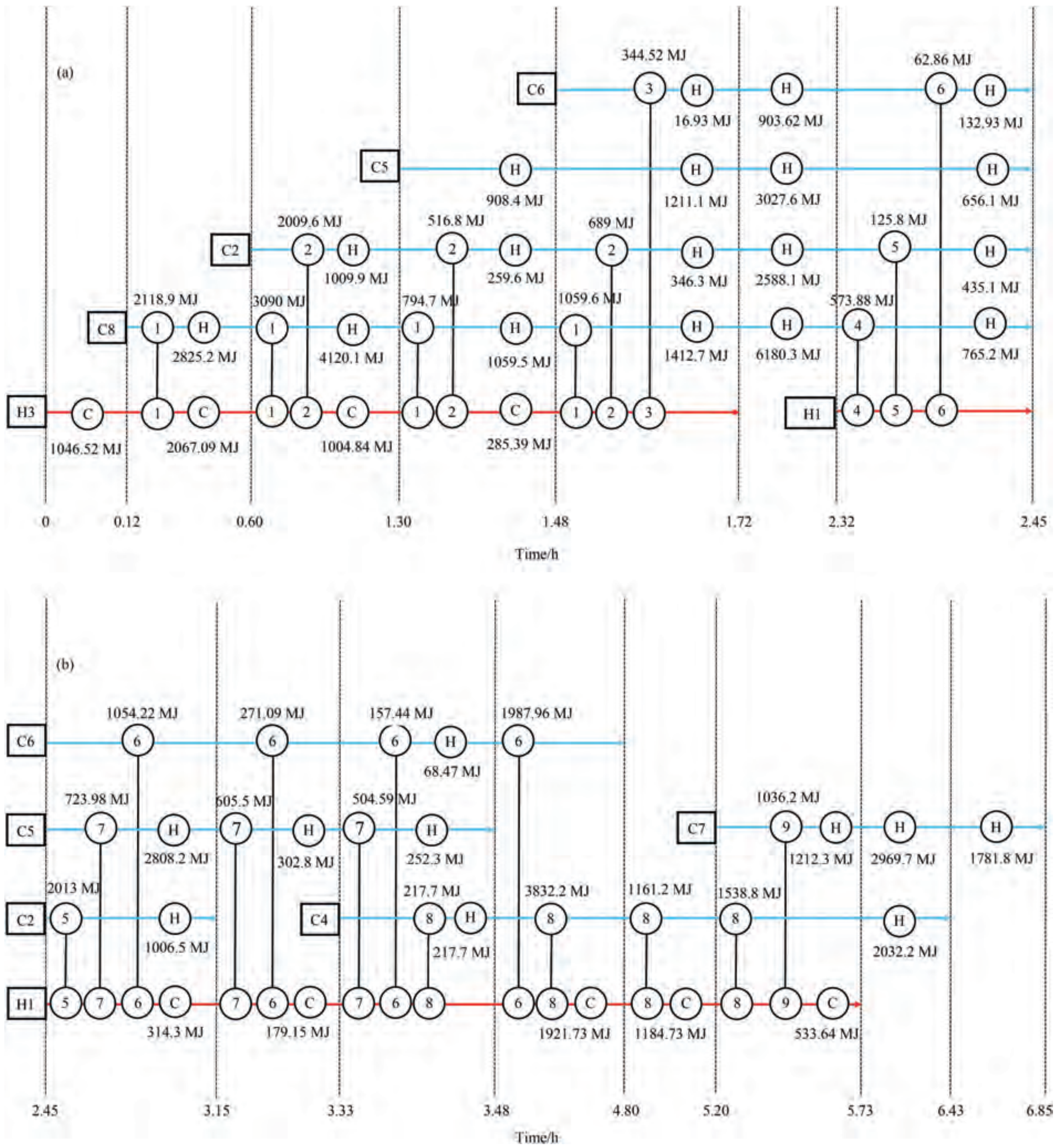

Fig. 10. Heat exchanger network of optimal scheduling of direct heat integration: (a) 0–2.45 h, (b) 2.3–6.85 h.

circular simultaneous optimization process, resulting in the following Table 9.

In this example, after the process scheduling of multi-product plant and the simultaneous optimization of heat integration, the energy saving achieved through multi-product plant scheduling and direct integration simultaneous optimization is 4799 MJ higher than that of sequential optimization of hot utility and cold utility, respectively. The percentages of saving hot utility and cold utility are increased by 7.1% and 13.7%, respectively. The EAP is increased by 43675 USD, and the ratio of EAP improvement is 6.4%. Similarly, the energy saving from multi-product plant scheduling and indirect heat integration simultaneous optimization is 94 MJ higher than that of sequential optimization. The EAP is increased by 31772 USD, and the ratio of EAP improvement is 4.7%. Furthermore, when comparing multi-product plant scheduling and indirect heat integration simultaneous optimization to direct heat integration simultaneous optimization, the energy saving is 3712 MJ higher for hot utility and cold utility combined. The percentages of saving hot utility and cold utility are increased by 5.6% and 10.7%, respectively. The EAP is increased by 7455 USD, and the ratio of EAP improvement is 1.1%. In Tables 8 and 9, despite the increase in equipment cost, the utility cost savings exceed 50%. The root cause of the small difference between the direct heat integration and the indirect heat integration strategies in the example 2 lies in the process characteristics. In this case, the direct heat integration's cold and hot stream matching accounts for the majority of the total stream matching, while the indirect heat integration's cold and hot stream matching accounts for a relatively

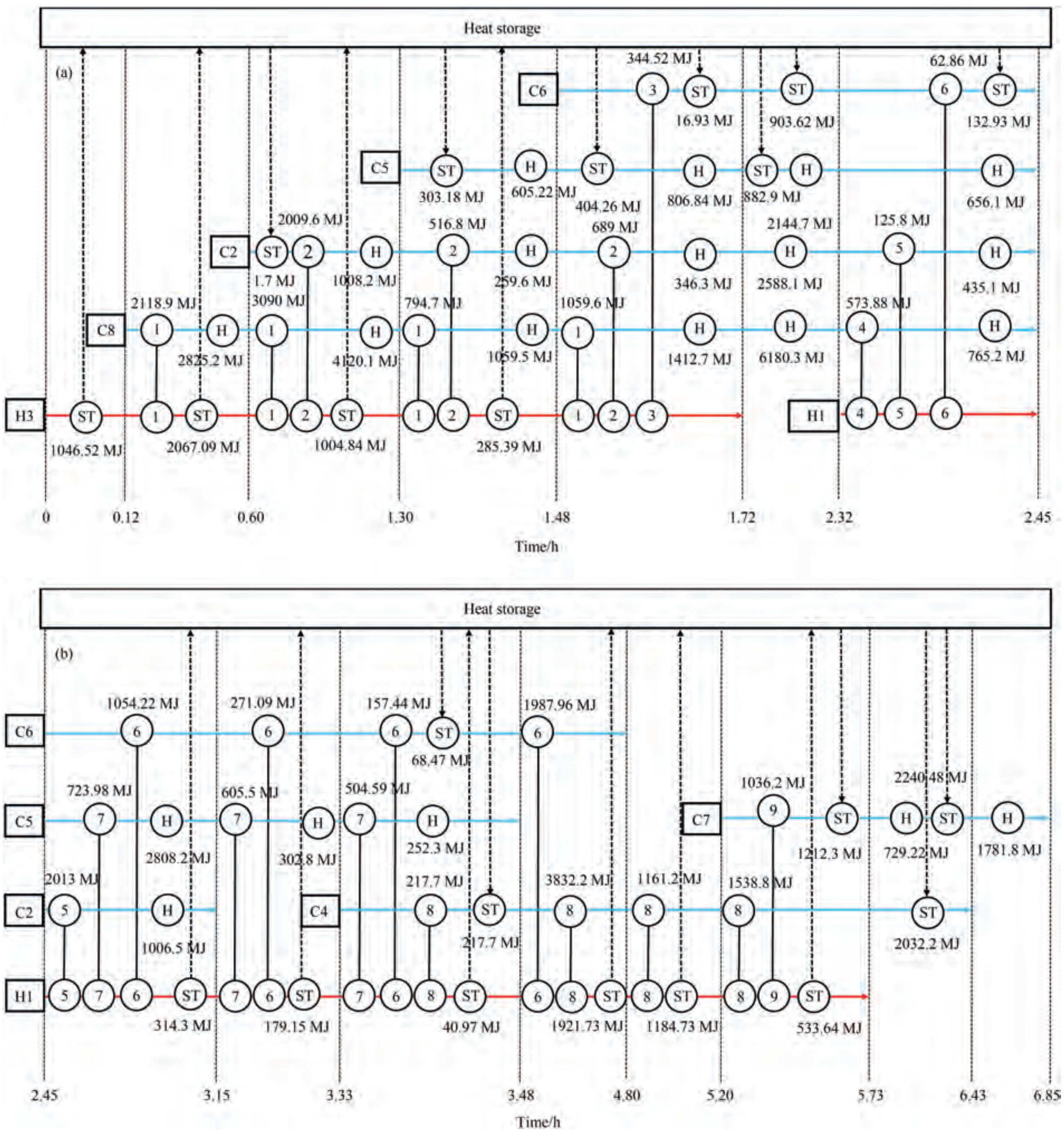

Fig. 11. Heat exchanger network of optimal scheduling of direct heat integration: (a) 0–2.45 h, (b) 2.3–6.85 h.

Table 8
Comparison of heat integration results.

	No integration	Direct heat integration	Direct + indirect heat integration
Hot utility/MJ	67000	40511	32094
Hot utility savings/MJ	0	26489	34906
Hot utility percentages of savings/%	0	39.5	52
Cold utility/MJ	35000	8511	94
Cold utility savings/MJ	0	26489	34906
Cold utility percentages of savings/%	0	75.6	99.7
Total cost of utilities/USD	682448	406909	319355
Number of heat exchangers	8	17	20
Number of heat storage tanks	0	0	3
Total cost of equipment/USD	32304	104585	172781
Energy-saving annual profit/USD	0	170954	190312
Energy-saving annual profit ratio/%	0	25	27.8

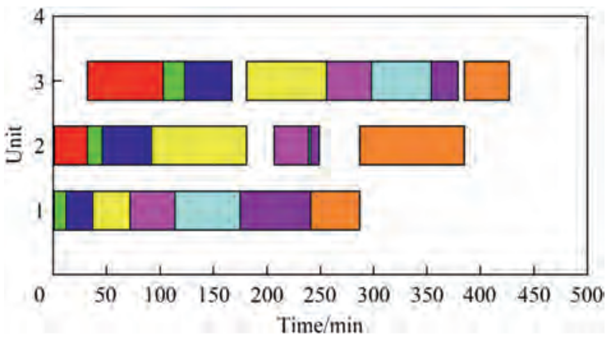

Fig. 12. Gantt chart of processing time of product.

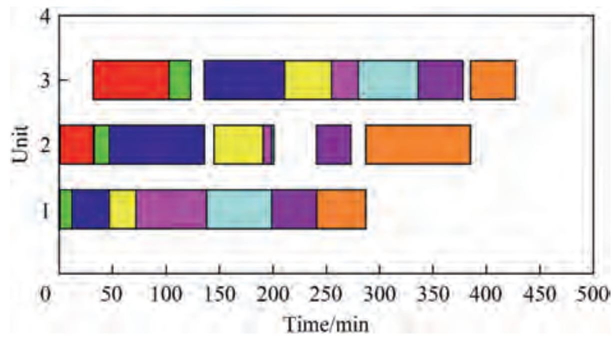

Fig. 14. Gantt chart of processing time of product.

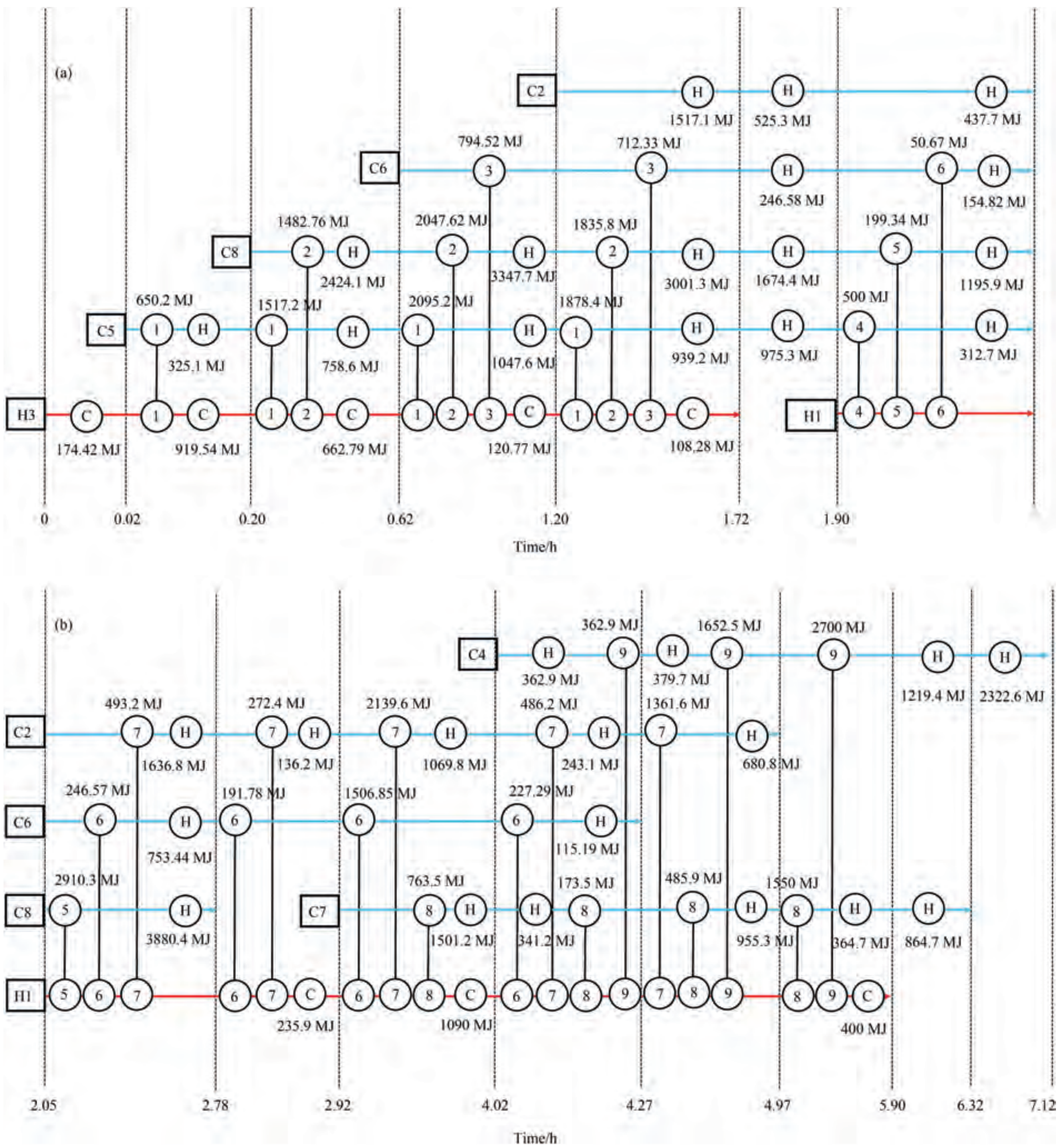

Fig. 13. Simultaneous optimization of heat exchanger network of direct heat integration: (a) 0–2.05 h, (b) 2.05–7.12 h.

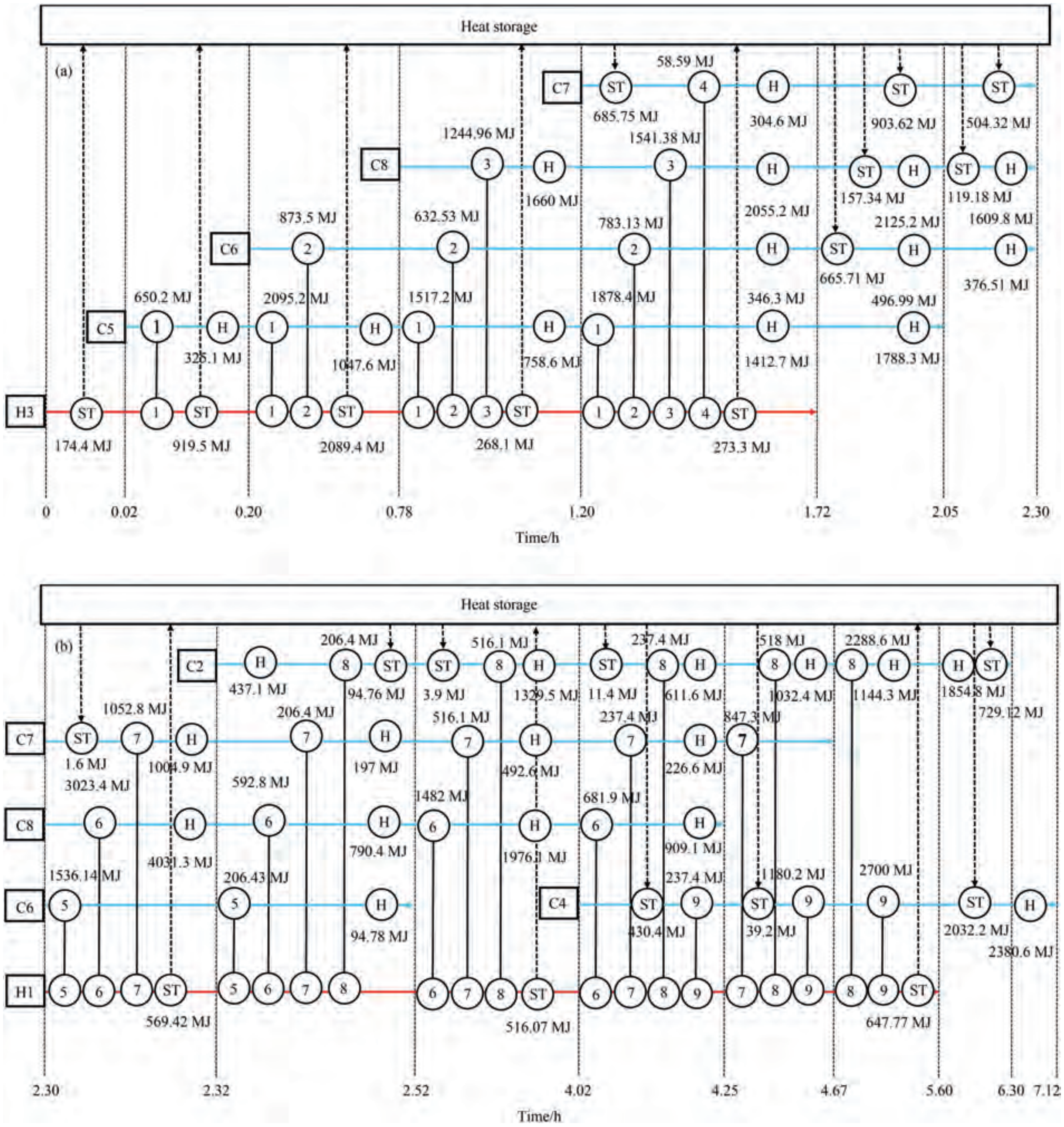

Fig. 15. Simultaneous optimization of heat exchanger network of indirect heat integration: (a) 0–2.3 h, (b) 2.3–7.12 h.

Table 9
Comparison of simultaneous optimization of heat integration results.

	No integration	Simultaneous optimization of direct heat integration	Simultaneous optimization of direct + indirect heat integration
Hot utility/MJ	67000	35712	32000
Hot utility savings/MJ	0	31288	35000
Hot utility percentages of savings/%	0	46.6	52.2
Cold utility/MJ	35000	3712	0
Cold utility savings/MJ	0	31288	35000
Cold utility percentages of savings/%	0	89.3	100
Total cost of utilities/USD	682448	343452	306304
Number of heat exchangers	8	17	22
Number of heat storage tanks	0	0	3
Total cost of equipment/USD	32304	124367	154060
Energy-saving annual profit/USD	0	214629	222084
Energy-saving annual profit ratio/%	0	31.4	32.5

small proportion. As a result, the improvement in EAP is minimal. Similarly, there is little difference between the simultaneous optimization method and the sequential optimization method in the example 2. If the quality of solution is high, the local optimal solution obtained through sequential optimization is closer to the global optimal solution achieved by simultaneous optimization, leading to a smaller improvement in EAP.

Through the above numerical results, the influence of different heat integration strategies on the overall operating efficiency and cost can be summarized. Through the above numerical results, the influence of different heat integration strategies on the overall operating efficiency and cost can be summarized. The direct heat integration method is suitable for continuous production scenarios (such as petrochemical and metallurgical) by directly matching cold and hot streams under conditions of time synchronization and temperature differences through heat exchangers. The heat recovery efficiency is 60% to 80%, which can save 15% to 25% compared to the investment of indirect heat integration equipment. However, the maintenance cost increases by 8% to 12% annually as the fouling rate of the heat exchanger increases [37,38]. On the other hand, the indirect heat integration method is suitable for multi-product batch production (such as food and pharmaceutical) by buffering the heat across time periods through heat storage tanks, allowing a synchronous time. Although the initial investment is 30% to 50% higher, the total cost can be reduced by 18% in the long term, and the energy utilization efficiency can increase by 40% when production fluctuates [39,40]. Therefore, in the context of carbon constraints, the direct method is preferred for continuous production systems to quickly reduce costs, while multi-product plants need to combine direct + indirect hybrid strategies (such as heat storage medium linkage) to balance economic resilience and energy efficiency.

5. Conclusions

This paper proposes an optimal scheduling and heat integration model for multi-product plants, solved using a bi-level programming method based on the genetic algorithm. This model maximizes heat recovery, determines the optimal scheduling time and minimum utility consumption, and optimizes heat storage for indirect heat integration to achieve the maximum EAP. Two examples show that the EAP of indirect heat integration considering the storage tank are 21% and 2% higher than that of the direct heat integration, and EAP of the simultaneous optimization are 26% and 6% higher than that of the sequential optimization. The example proves the feasibility and effectiveness of the algorithm and model. At present, more researchers are focusing on the optimization of scheduling structures for batch process, yet research on scheduling and heat integration for batch process remains insufficient. The dual carbon targets—carbon peaking and carbon neutrality—are China's national strategies to address climate change and promote green and low-carbon development. Promoting the application and in-depth research of scheduling and heat integration is an imperative measure in response to these national strategic approaches. In view of the current research status, the following problems still persist in the field of scheduling and heat integration for batch process: (1) Currently, most researchers only consider economic profit as the objective, and the content of multi-objective optimization, which takes into account both economic profit and environmental factors, requires further study. (2) At present, most researchers only consider equipment failure and order changes in scheduling, and the expansion of heat integration to account for these factors necessitates theoretical research support.

CRediT Authorship Contribution Statement

Ke Li: Writing – review & editing, Writing – original draft. Lingqi Kong: Conceptualization. Xinping Wang: Formal analysis. Mengyu Liu: Formal analysis.

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.

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