Heat integration in multipurpose batch plants using a robust scheduling framework

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Abstract

Energy saving is becoming increasingly important in batch processing facilities. Multipurpose batch plants have become more popular than ever in the processing environment due to their inherent flexibility and adaptability to market conditions, even though the same flexibility may lead to complexities such as the need to schedule process tasks. These are important features to producing high value added products such as agrochemicals, pharmaceuticals, polymers, food and specialty chemicals where the demand has grown in recent decades. Many current heat integration methods for multipurpose batch plants use a sequential methodology where the schedule is solved first followed by heat integration. This can lead to suboptimal results. In this paper, the heat integration model is built upon a robust scheduling framework. This scheduling formulation has proven to lead to better results in terms of better objective values, fewer required time points and reduced computational time. This is important as inclusion of heat integration into a scheduling model invariably complicates the solution process. The improved scheduling model allows the consideration of industrial sized problems to simultaneously optimize both the process schedule and energy usage. Both direct and indirect heat integration are considered as well as fixed and variable batch sizes.

Keywords: Heat integration, Scheduling, Multipurpose batch plants, Energy optimization

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1. Introduction

Batch processing is commonly used, when products are required in small quantities or when the processes are complex or specialized, to manufacture high value added products. Examples include food, pharmaceuticals, fine chemicals, biochemicals and agrochemicals. Batch operations, even though they are becoming increasingly popular, are generally run on a smaller scale compared to continuous operations, and utility requirements are therefore considered less significant. However, the utility requirements for the food industry, breweries, dairies, meat processing facilities, biochemical plants and agrochemical facilities contribute largely to their overall cost [1]. Energy savings have often been neglected in batch processes in the past and hence significant savings are possible. The literature review is organized into two major sections and includes methods developed in the 20th and 21st centuries.

1.1. Methods and models developed in the 20th century

Early work that aimed at reducing energy consumption in batch plants was by adopting methods that had been developed for continuous processing plants. One of the very first contributions in this regard for energy integration in batch plants was through applying the principle of time average model (TAM)[2]. However, this approach does not consider the process schedule, and assumes that the hot and cold streams exist simultaneously as incontinuous processes. The identified energy targets could not be achieved when only direct heat integration was applied since the time schedule is not considered. The TAM formulation was further extended to incorporate heat storage to achieve the maximum energy saving targets [3]. Vaselenak et al. [4] explored the possibility of heat recovery between a number of tanks which required heating and cooling through the consideration of co-current, counter-current and a combination of the two. The authors did not account for the time schedule; they assumed that all tanks are available at the same time. In order to address the limitations of the TAM, various works considered the time schedule in the heat integration analysis. The work on design of batch processes based on pinch technology showed that the cost structure should consider the interaction between capital, energy, scheduling and yields in order to address the wider scope [5]. The cascade analysis for maximum heat recovery based on time temperature cascade tables that consider both direct and indirect heat exchange between streams was developed [6]. A strategy for creating schedules of maximum power of heat integration which ensures, on the one hand, production targets and on the other hand, optimal condition for heat integration was demonstrated [7] and a methodology was presented to address the important aspect of rescheduling for maximum energy recovery [8]. Different theoretical aspects of optimal energy integration in batch chemical plants have been considered in the previous literature, with little experience on real case studies. This gap was addressed by applying optimal energy integration formulation for an existing antibiotics plant where implementation of the formulation gave an overall energy cost reduction of 39% [9]. Most of the research work mentioned above is based on fixed production schedules that already achieve all the plant objectives and minimize the energy requirement afterward. However, in general, even optimal production schedules tend to be quite degenerate, in the sense that there often exist a large number of different schedules, all of which can achieve a given set of production requirements. Nevertheless, the potential for heat integration could vary significantly from one such schedule to another. Consequently, heat integration should be considered as an integral part of the problem of scheduling the production in a given plant. The cost of utilities should be incorporated within the overall economic objective of maximizing the net value of the production over a given time horizon and solved simultaneously [10]. There were other studies that resolved the heat integration in batch processes by establishing an objective that was to minimize the combined operating and annualized capital costs of the heat exchanger networks (HENs) for a class of multipurpose batch plants. A mathematical formulation that selects the production campaigns and designs HENs simultaneously has been presented [11]. However, the formulation limits a heat exchanger to be used for a specific pair of processing units. Design of HENs for a system of batch vessels that exploits heat integration potential with minimum cost has also been developed [12].

1.2. Methods and models developed in the 21st century

The research conducted in this century has been concentrated on improving the models and methodologies that had been proposed previously as well as the optimization of heat integration in batch processes through the development of new tools such as genetic algorithms and network evolution techniques. Moreover, there has been a significant increase in the utilization of thermal storage to improve heat integration in a discontinuous process.

1.2.1. Models developed for direct heat integration

The developed models in this category require the hot and cold task should be operated in the same time interval for the heat exchange to occur. Uhlenbruck et al. [13] improved OMNIUM, which is a tool, developed for heat exchanger network synthesis by Hellwig and Thone [14]. The improved OMNIUM tool increased the energy recovery by 20%. A single step, interactive computer program (BatcHEN) used for the determination of the campaigns (i.e. the set of products which can be produced simultaneously), the heat exchange areas of all possible heat exchangers in the campaigns and the heat exchanger network was presented [15]. This work addressed the limitation of the graph theory method [11] for the determination of the campaign where it is very complex for handling large numbers of products and process units. A heat integration model based on S-graph scheduling framework approaches was developed [16]. Results of this paper showed how utility usage can be reduced considerably with just a slight increase in production makespan. Morrison et al. [17] developed a user-friendly software package known as Optimal Batch Integration (OBI). Chen and Chang [18] integrated the task scheduling and heat recovery problems into a unified framework for multipurpose batch processes. The batch scheduling formulation is extended from the continuous Resource Task Network (RTN) formulation which was originally proposed by Castro et al. [19]. Halim and Srinivasan [20] discussed a sequential method using direct heat integration. A number of optimal schedules with minimum makespan were found, and heat integration analysis was performed on each. The schedule with minimum utility requirement was chosen as the best. Later, Halim and Srinivasan [21] extended their technique to carry out water reuse network synthesis simultaneously. One key feature of this method is its ability to find the heat integration and water reuse solution without much sacrificing the quality of the scheduling solution as compared to other sequential techniques for heat integration for multipurpose batch plants.

There are other works that considered energy saving and the capital cost associated to heat exchanger to achieve the minimum utility target. The technique for design and synthesis of batch plant [22] was later extended to incorporate economic savings in utility requirements, while considering both the cost of the auxiliary structures (i.e. heat exchangers through their transfer area) and the design of the utility circuits and associated piping costs [23]. Liu et al. [24] formulated a batch heat exchanger network that results in nonlinear programming (NLP). The application of the formulation has demonstrated that it can effectively reduce the annual capital cost and annual total cost of HEN with the employment of common heat exchangers. Maiti et al. [25] developed a novel heat integrated batch distillation column in order to improve the thermal efficiency and reduce the total annual cost. The potential energy integration leads to achieving approximately 56.10% energy savings and 40.53% savings in total annual cost.

1.2.2. Models developed for indirect heat integration

Models developed in this category used heat storage for a more heat recovery and flexible schedule compared to direct heat integration methods. The use of heat storage allows the exchange of heat from hot task to cold task to takes place in different time interval. A systematic procedure based on pinch analysis, backed with a graphical representation, allows the determination of the minimum number of heat storage units and their range of feasible operation as a function of the amount of heat recovery was presented [26]. Chen and Ciou [27] formulated a method to design and optimize indirect energy storage systems for batch processes. Their work aimed at simultaneously solving the problem of indirect heat exchange network synthesis and its associated thermal storage policy for recirculated hot/cold heat storage medium (HEN). Most of the previous work solved this sequentially. The BatchHeat software, whose aim was to highlight the energy inefficiencies in the process and thereby enabling the scope for possible heat recovery to be established through direct heat exchange or storage through implementation of cascade analysis, was developed [28].

1.2.3. Models applied for real industrial case studies

This section presented methodologies developed for energy recovery taking existing batch processing plans. The application of cascade analysis proposed by Kemp and Macdonald [29] to reduce the utility requirement was applied to an industrial case study which produces oleic acid from palm olein using immobilized lipase [30]. The result obtained showed savings of 71.4% and 62.5% for hot and cold utilities, respectively. Application of process integration to investigate the potential to decrease the energy usage in the slaughtering and meat processing industry was studied. Above ambient temperatures, heating of water with different target temperatures is a large heat demand in a plant, while at subambient temperatures the refrigeration plant needs almost all of the shaftwork used at the site. Interaction between, on one hand, energy demands above ambient temperature, and on the other hand, cooling needs below ambient temperature can take place with freezing compressors or heat pumps. The result obtained illustrates that 30% of the external heat demand and more than 10% of the shaftwork used can be saved [31].

Majozi [32] presented a heat integration model for multipurpose batch plants based on the continuous-time scheduling framework [33]. The formulation results in smaller problems compared to the discrete-time formulation, which renders it applicable to large-scale problems. Application of the formulation to an agro chemical industrial case study showed an 18.5% improvement in profit. The direct heat integration model [32] was extended to incorporate heat storage for more flexible schedules and utility savings in the later work by Majozi [34]. However, the storage size is a parameter in his formulation which is addressed later by Stamp and Majozi [1], where the storage size is determined by an optimization exercise. Foo et al. [35] extended the minimum units targeting and network evolution techniques that were developed for batch mass exchange network (MEN) into batch HEN. They applied the technique for energy integration of oleic acid production from palm olein using immobilized lipase. Atkins et al. [36] applied indirect heat integration using heat storage for a milk powder plant in New Zealand. The traditional composite curves have been used to estimate the maximum heat recovery and to determine the optimal temperatures of the stratified tank. Tokos et al. [37] applied a batch heat integration technique to a large beverage plant. The opportunities of heat integration between batch operations were analyzed by a mixed integer linear programming (MILP) model, which was slightly modified by considering specific industrial circumstances. Muster-Slawitsch et al. [38] came up with the Green Brewery concept to demonstrate the potential for reducing thermal energy consumption in breweries. Three detailed case studies have been performed. The Green Brewery concept has shown a saving potential of over 5000 ton/y fossil CO_2 emissions from thermal energy supply for the three breweries that were closely considered. Becker [39] applied time average energy integration approach to a real case study of a cheese factory with non-simultaneous process operations. Their work addressed appropriate heat pump integration. A cost saving of more than 40% was reported. Integration of solar thermal energy in a batch fish tinning processes was investigated. The work demonstrated the most favorable heat integration option for the thermosolar and heat pump [40]. Recently a design model for heat recovery, using heat storage and integration of industrial solar for a case study of dairy processing, was developed. Application of the model gave 37% heat recovery [41]. The reader can get a more comprehensive and detailed review on energy recovery for batch processes in the paper by Fernández et al. [42].

Many heat integration techniques are applied to predefined schedules which may leads to suboptimal results. For a more optimal solution, scheduling and heat integration should be combined into an overall problem and solved simultaneously. This work aims to improve the efficiency of energy integration techniques by developing a single framework that contains scheduling and heat integration models for multipurpose batch plants to be solved simultaneously for an optimal solution. A recent robust scheduling formulation by Seid and Majozi [43] is used as a platform since it has proven to require fewer time points and reduced computational time compared to other models and may also lead to an improved objective value. Compared to other models based on simultaneous approach for heat integration for multipurpose batch plants, the developed model allows a task to be heat integrated with other tasks in more than one time interval during its starting and finishing times for better heat recovery. Additionally, this work generalizes the heat integration problem with the considerations of temperature change during processing of tasks and heat integration to occur in any interval between the starting and finishing time of a task which is a limitation of the recent work by Stamp and Majozi [1]. It also caters for availability of heat storage for indirect heat integration which is a limitation of the more advanced sequential methodology for heat integration by Halim and Srinivasan [20]. Most literature has addressed these problems independently.

The subsequent sections are organized as follows. The problem statement and objectives are given in the next section. The developed mathematical model is then discussed in Section 3. The model is then applied to three literature examples and the results are compared to recent literature models in Section 4. Conclusions are then drawn to highlight the value of the contribution in Section 5.

2. Problem statement and objectives

The problem addressed in this work can be stated as follows.

Given:

(i) Production scheduling data, including equipment capacities, durations of tasks, time horizon of interest, product recipes, cost of starting materials and selling price of final products,

(ii) Hot duties for tasks requiring heating and cold duties for tasks that require cooling,

(iii) Costs of hot and cold utilities,

(iv) Operating temperatures of tasks requiring heating and cooling,

(v) Minimum allowable temperature differences, and

(vi) Design capacity limits on heat storage,

Determine:

(i) An optimal production schedule where the objective is to maximize profit, defined as the difference between revenue and the cost of hot and cold utilities.

(ii) The size of heat storage as well as the initial temperature of heat storage.

3. Mathematical formulation

3.1. Model constraints

The scheduling model by Seid and Majozi [43] is adopted since it has proven to result in fewer binary variables, reduced CPU time and a better optimal objective value compared to other scheduling models.

The mathematical model is based on the superstructure in Figure 1. Each task may operate using either direct or indirect heat integration. Tasks may also operate in standalone mode, using only external utilities. This may be required for control reasons or when thermal driving forces or time do not allow for heat integration. If either direct or indirect heat integration is not sufficient to satisfy the required duty, external utilities may be used to make up the deficit.

Constraints (1) and (2) are active simultaneously and ensure that one hot unit can only be integrated with one cold unit when direct heat integration takes place, in order to avoid operational complexity of the process. However, It is also possible for one unit to integrate with more than one unit at a given time point simultaneously when the summation notation in the equations are not used. Also, if two units are to be heat integrated at a given time point, they must both be active at that time point.

$$\sum_{s_{injc}} x(s_{injc}, s_{injh}, p, pp) \leq y(s_{injh}, p),$$

$$\forall p, pp \in P,\ s_{injh} \in S_{inJ_h},\ s_{injc} \in S_{inJ_c} \quad (1)$$

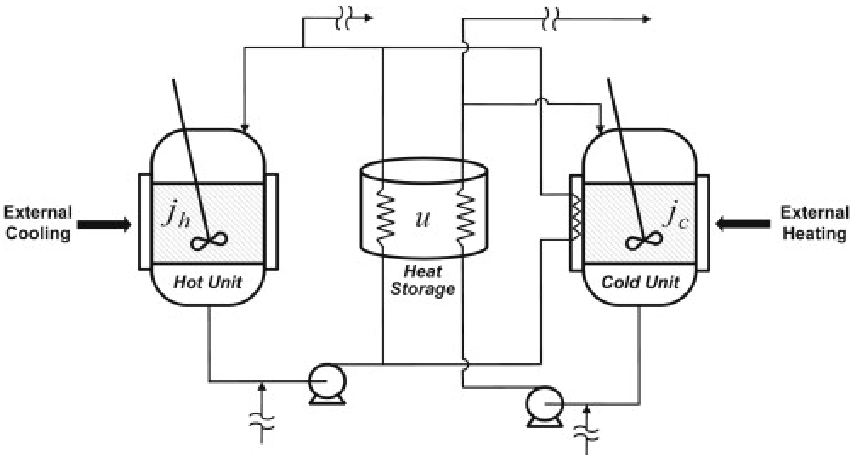


Figure 1: Superstructure for mathematical model.

$$\sum_{s_{inj_h}} x(s_{inj_c}, s_{inj_h}, p, pp) \leq y(s_{inj_c}, p),$$
$$\forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (2)$$

For better understanding, the difference between time point p and extended time point pp is explained using Figure 2. If a unit j that is active at time point p is integrated with more than one unit in different temperature and time intervals, an extended time point pp must be defined. Unit $j1$ active at time point p can be integrated with units $j2$ and $j3$ in different time and temperature intervals. At the beginning, unit $j1$ is integrated with unit $j2$ at time point p and the extended time point pp is the same as time point p. Later, $j1$ is integrated with unit $j3$ in another time interval where extended time point pp equals to $p + 1$. pp is equal to or greater than time point p and less than or equal to $n+p$, where n is a parameter which is greater than or equal to zero. If n equals 2 then a unit that is active at time point p can be integrated in three different time intervals. The model should be solved starting from n equals zero and adding one at a time until no better objective value is achieved. This concept is the novelty of this work which addresses the limitation of models based on simultaneous approach for heat integration for multipurpose batch plants where a task is allowed to be heat integrated with other tasks only for one time interval during the starting and finishing time of the task.

Constraints (3) and (4) ensure that a unit cannot undergo direct and indirect heat integration simultaneously. This condition simplifies the operation of the process.

$$\sum_{s_{inj_h}} x(s_{inj_c}, s_{inj_h}, p, pp) + z(s_{inj_c}, u, p, pp) \leq 1,$$
$$\forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c},\ u \in U \quad (3)$$

$$\sum_{s_{inj_c}} x(s_{inj_c}, s_{inj_h}, p, pp) + z(s_{inj_h}, u, p, pp) \leq 1,$$
$$\forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c},\ u \in U \quad (4)$$

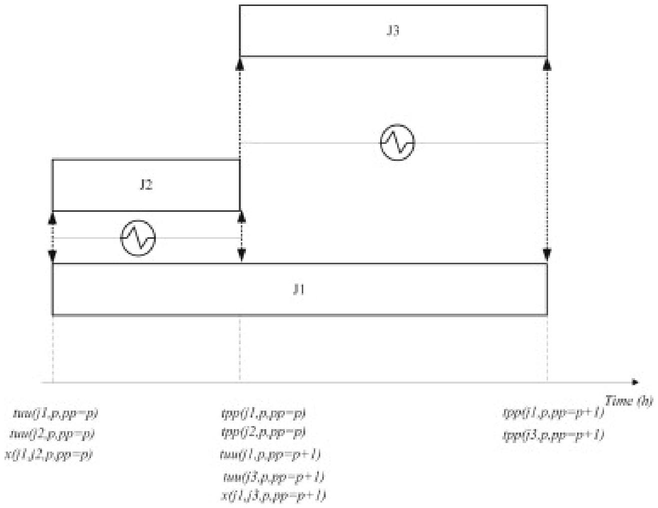


Figure 2: Differentiating time point p and extended time point pp.

Constraint (5) describes the amount of cooling load required by the hot unit to reach from its initial temperature to its target temperature. On an occasion where the temperature in the reactor unit is to be fixed during exothermic reaction, the heat load becomes the product of the amount of mass that undergoes reaction and the heat of reaction.

$$cl(s_{inj_h}, p) = mu(s_{inj_h}, p)cp(s_{inj_h}) \\ (T^{in}_{s_{inj_h}} - T^{out}_{s_{inj_h}}),\ \forall p \in P,\ s_{inj_h} \in S_{inJ_h} \quad (5)$$

Constraint (6) describes the heating load required by the cold unit to reach from its initial temperature to its target temperature. On an occasion where the temperature in the reactor unit is to be fixed during endothermic reaction, the heat load becomes the product of the amount of mass that undergoes reaction and the heat of reaction.

$$hl(s_{inj_c}, p) = mu(s_{inj_c}, p)cp(s_{inj_c}) \\ (T^{out}_{s_{inj_c}} - T^{in}_{s_{inj_c}}),\ \forall p \in P,\ s_{inj_c} \in S_{inJ_c} \quad (6)$$

Constraints (7) and (8) describe the average heat flow for the hot and cold unit, respectively, during the processing time, which is the same as time average model (TAM) to address the energy balance during heat integration properly.

$$cl(s_{inj_h}, p) = avcl(s_{inj_h}, p)(tp(s_{inj_h}, p)- \\ tu(s_{inj_h}, p)),\ \forall p \in P,\ s_{inj_h} \in S_{inJ_h} \quad (7)$$

$$hl(s_{inj_c}, p) = avhl(s_{inj_c}, p)(tp(s_{inj_c}, p)- \\ tu(s_{inj_c}, p)),\ \forall p \in P,\ s_{inj_c} \in S_{inJ_c} \quad (8)$$

Constraints (9) and (10) define the heat load at time point *p* and extended time point *pp* for the cold and hot unit.

$$hlp(s_{inj_c}, p, pp) = avhl(s_{inj_c}, p)(tpp(s_{inj_c}, p, pp)- \\ tuu(s_{inj_c}, p, pp)), \\ \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c} \quad (9)$$

$$clp(s_{inj_h},p,pp) = avcl(s_{inj_h},p)(tpp(s_{inj_h},p,pp) - tuu(s_{inj_h},p,pp)), \quad \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h} \quad (10)$$

Constraints (11) and (12) quantify the amount of heat received from and transferred to the heat storage unit, respectively. There will be no heat received or transferred if the binary variable signifying use of the heat storage vessel, $z(s_{inj},u,p,pp)$, is zero.

$$Q(s_{inj_c},u,p,pp) = W(u)cp(u)(T_0(u,p,pp) - T_f(u,p,pp))z(s_{inj_c},u,p,pp), \quad \forall p \in P,\ s_{inj_c} \in S_{inJ_c},\ u \in U \quad (11)$$

$$Q(s_{inj_h},u,p,pp) = W(u)cp(u)(T_f(u,p,pp) - T_0(u,p,pp))z(s_{inj_h},u,p,pp), \quad \forall p \in P,\ s_{inj_h} \in S_{inJ_h},\ u \in U \quad (12)$$

Constraints (13) and (14) are used to calculate the temperature of the hot and cold unit at the intervals.

$$clp(s_{inj_h},p,pp) = mu(s_{inj_h},p)cp(s_{inj_h})(T^{in}(s_{inj_h},p,pp) - T^{out}(s_{inj_h},p,pp)), \quad \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h} \quad (13)$$

$$hlp(s_{inj_c},p,pp) = mu(s_{inj_c},p)cp(s_{inj_c})(T^{out}(s_{inj_c},p,pp) - T^{in}(s_{inj_c},p,pp)), \quad \forall p,pp \in P, s_{inj_c} \in S_{inJ_c} \quad (14)$$

Constraint (15) states that the amount of heat exchanged between the cold unit and the heat storage should be less than the heat load required by the cold unit during the interval.

$$Q(s_{inj_c},u,p,pp) \leq hlp(s_{inj_c},p,pp), \quad \forall p,pp \in P,\ s_{inj_c} \in S_{inJ_c},\ u \in U \quad (15)$$

Constraint (16) states that the amount of heat exchanged between the hot unit and the heat storage should be less than the cooling load required by the hot unit during the interval.

$$Q(s_{inj_h},u,p,pp) \leq clp(s_{inj_h},p,pp), \quad \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ u \in U \quad (16)$$

Constraint (17) states that the amount of heat exchanged between the hot and the cold units should be less than the cooling load required by the hot unit during the interval.

$$\sum_{s_{inj_c}} Qe(s_{inj_h},s_{inj_c},p,pp) \leq clp(s_{inj_h},p,pp), \quad \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (17)$$

Constraint (18) states that the amount of heat exchanged between the cold unit and the hot units should be less than the heat load required by the cold unit during the interval.

$$\sum_{s_{inj_h}} Qe(s_{inj_h},s_{inj_c},p,pp) \leq hlp(s_{inj_c},p,pp), \quad \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (18)$$

Constraint (19) ensures that if heat integration occurs, the heat load should have a value that is less than the maximum amount of heat exchangeable. When the binary variable associated with heat integration takes a value of zero, no heat integration occurs and the associated heat load is zero.

$$Qe(s_{injh}, s_{injc}, p, pp) \leq Q^U x(s_{injc}, s_{injh}, p, pp), \quad \forall p, pp \in P,\ s_{injh} \in S_{inJ_h},\ s_{injc} \in S_{inJ_c} \quad (19)$$

Constraints (20) and (21) ensure that if heat integration between the cold and hot units takes place with the heat storage, then the heat load takes a positive value. This only happens when the binary variable associated with integration of cold and hot units with the heat storage unit takes a value of one.

$$Q(s_{injh}, u, p, pp) \leq Q^U z(s_{injh}, u, p, pp), \quad \forall p, pp \in P,\ s_{injh} \in S_{inJ_h},\ u \in U \quad (20)$$

$$Q(s_{injc}, u, p, pp) \leq Q^U z(s_{injc}, u, p, pp), \quad \forall p, pp \in P,\ s_{injc} \in S_{inJ_c},\ u \in U \quad (21)$$

Constraints (22) and (23) state that the temperature of the task at the current time interval should be equal to the temperature at the end of the previous time interval.

$$T^{in}(s_{injh}, p, pp) = T^{out}(s_{injh}, p, pp-1), \quad \forall p, pp \in P,\ s_{injh} \in S_{inJ_h} \quad (22)$$

$$T^{in}(s_{injc}, p, pp) = T^{out}(s_{injc}, p, pp-1), \quad \forall p, pp \in P,\ s_{injc} \in S_{inJ_c} \quad (23)$$

Constraint (24) states that the temperature of the heat storage unit at the current time interval should be equal to the temperature at the end of the previous time interval.

$$T_o(u, p, pp) = T_f(u, p, pp-1), \quad \forall p, pp \in P,\ u \in U \quad (24)$$

Constraint (25) states that the initial temperature of the heat storage unit at the current time point p should be equal to the final temperature at the previous time point $p-1$.

$$T_o(u, p, pp=p) = T_f(u, p-1, pp=p-1+n), \quad \forall p, pp \in P \quad (25)$$

Constraints (26) and (27) state that the temperature at the start of the first time interval, which is time point p, and also pp, should be equal to the initial temperature of the task.

$$T^{in}(s_{injh}, p, pp) = T^{in}_{s_{injh}}, \quad \forall p, pp \in P,\ s_{injh} \in S_{inJ_h} \quad (26)$$

$$T^{in}(s_{injc}, p, pp) = T^{in}_{s_{injc}}, \quad \forall p, pp \in P,\ s_{injc} \in S_{inJ_c} \quad (27)$$

Constraints (28) and (29) ensure that the minimum thermal driving forces are obeyed when there is direct heat integration between a hot and a cold unit.

$$T^{in}(s_{inj_h}, p, pp) - T^{out}(s_{inj_c}, p, pp) \geq \\ \triangle T - \triangle T^{U}(1 - x(s_{inj_c}, s_{inj_h}, p, pp)), \\ \forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (28)$$

$$T^{out}(s_{inj_h}, p, pp) - T^{in}(s_{inj_c}, p, pp) \geq \\ \triangle T - \triangle T^{U}(1 - x(s_{inj_c}, s_{inj_h}, p, pp)), \\ \forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (29)$$

Constraints (30) and (31) ensure that the minimum thermal driving forces are obeyed when there is direct heat integration between a hot task and a heat storage unit.

$$T^{in}(s_{inj_h}, p, pp) - T_f(u, p, pp) \geq \\ \triangle T - \triangle T^{U}(1 - z(s_{inj_h}, u, p, pp)), \\ \forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ u \in U \quad (30)$$

$$T^{out}(s_{inj_h}, p, pp) - T_o(u, p, pp) \geq \\ \triangle T - \triangle T^{U}(1 - z(s_{inj_h}, u, p, pp)), \\ \forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h} \quad (31)$$

Constraints (32) and (33) ensure that the minimum thermal driving forces are obeyed when there is direct heat integration between a cold task and a heat storage unit.

$$T_o(u, p, pp) - T^{out}(s_{inj_c}, p, pp) \geq \\ \triangle T - \triangle T^{U}(1 - z(s_{inj_c}, u, p, pp)), \\ \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c},\ u \in U \quad (32)$$

$$T_f(u, p, pp) - T^{in}(s_{inj_c}, p, pp) \geq \\ \triangle T - \triangle T^{U}(1 - z(s_{inj_c}, u, p, pp)), \\ \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c} \quad (33)$$

Constraints (34) and (35) state that temperatures change in the heating and cooling unit when the binary variables associated with heating and cooling are active.

$$T^{in}(s_{inj_h}, p, pp) - T^{out}(s_{inj_h}, p, pp) \leq \\ \triangle T^{U} v(s_{inj_h}, p, pp), \\ \forall p, pp \in P, s_{inj_h} \in S_{inJ_h} \quad (34)$$

$$T^{out}(s_{inj_c}, p, pp) - T^{in}(s_{inj_c}, p, pp) \leq \\ \triangle T^{U} v(s_{inj_c}, p, pp), \\ \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c} \quad (35)$$

Constraints (36) and (37) state that temperatures change in the heat storage unit when the binary variables associated with heating and cooling with the heat storage unit are active.

$$T^{out}(u, p, pp) - T^{in}(u, p, pp) \leq \\ \triangle T^{U}(\sum_{s_{inj_c}} z(s_{inj_c}, u, p, pp) + \\ \sum_{s_{inj_h}} z(s_{inj_h}, u, p, pp)), \\ \forall p, pp \in P, s_{inj_h} \in S_{inJ_h}, s_{inj_c} \in S_{inJ_c}, u \in U \quad (36)$$

$$T^{out}(u,p,pp) - T^{in}(u,p,pp) \geq \\ -\triangle T^{U}(\sum_{s_{injc}} z(s_{inj_c},u,p,pp) + \\ \sum_{s_{inj_h}} z(s_{inj_h},u,p,pp)), \\ \forall p,pp \in P,\, s_{inj_h} \in S_{inJ_h},\, s_{inj_c} \in S_{inJ_c},\, u \in U \tag{37}$$

Constraints (38), (39), (40) and (41) ensure that the times at which units are active are synchronized when direct heat integration takes place.

$$tuu(s_{inj_h},p,pp) \geq tuu(s_{inj_c},p,pp) - \\ M(1 - x(s_{inj_c},s_{inj_h},p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \tag{38}$$

$$tuu(s_{inj_h},p,pp) \leq tuu(s_{inj_c},p,pp) + \\ M(1 - x(s_{inj_c},s_{inj_h},p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \tag{39}$$

$$tpp(s_{inj_h},p,pp) \geq tpp(s_{inj_c},p,pp) - \\ M(1 - x(s_{inj_c},s_{inj_h},p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_h} \tag{40}$$

$$tpp(s_{inj_h},p,pp) \leq tpp(s_{inj_c},p,pp + \\ M(1 - x(s_{inj_c},s_{inj_h},p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \tag{41}$$

Constraints (42), (43), (44), (45), (46), (47), (48) and (49) ensure that the times at which the cold and hot units are synchronized with the time of the heat storage unit when heat integration takes place.

$$tuu(s_{inj_h},p,pp) \geq tuu(u,p,pp) - \\ M(2 - v(s_{inj_h},p,pp) - z(s_{inj_h},u,p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ u \in U \tag{42}$$

$$tuu(s_{inj_h},p,pp) \leq tuu(u,p,pp) + \\ M(2 - v(s_{inj_h},p,pp) - z(s_{inj_h},u,p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ u \in U \tag{43}$$

$$tpp(s_{inj_h},p,pp) \geq tpp(u,p,pp) - \\ M(2 - v(s_{inj_h},p,pp) - z(s_{inj_h},u,p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ u \in U \tag{44}$$

$$tpp(s_{inj_h},p,pp) \leq tpp(u,p,pp) + \\ M(2 - v(s_{inj_h},p,pp) - z(s_{inj_h},u,p,pp)), \\ \forall p,pp \in P,\ s_{inj_h} \in S_{inJ_h},\ u \in U \tag{45}$$

$$tuu(s_{inj_c},p,pp) \geq tuu(u,p,pp) - \\ M(2 - v(s_{inj_c},p,pp) - z(s_{inj_c},u,p,pp)), \\ \forall p,pp \in P, in\ s_{inj_c} \in S_{inJ_c},\ u \in U \tag{46}$$

$$tuu(s_{inj_c},p,pp) \leq tuu(u,p,pp) + \\ M(2 - v(s_{inj_c},p,pp) - z(s_{inj_c},u,p,pp)), \\ \forall p,pp \in P,\ s_{inj_c} \in S_{inJ_c},\ u \in U \tag{47}$$

$$tpp(s_{inj_c}, p, pp) \geq tpp(u, p, pp) - M(2 - v(s_{inj_c}, p, pp) - z(s_{inj_c}, u, p, pp)), \quad \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c},\ u \in U \tag{48}$$

$$tpp(s_{inj_c}, p, pp) \leq tpp(u, p, pp) + M(2 - v(s_{inj_c}, p, pp) - z(s_{inj_c}, u, p, pp)), \quad \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c},\ u \in U \tag{49}$$

Constraints (50) and (51) state that the starting time of the heating load required for the cold unit and the cooling load required for the hot unit at the first time interval should be equal to the starting time of the hot and cold unit.

$$tuu(s_{inj_h}, p, pp = p) = tu(s_{inj_h}, p), \quad \forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h} \tag{50}$$

$$tuu(s_{inj_c}, p, pp = p) = tu(s_{inj_c}, p), \quad \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c} \tag{51}$$

Constraints (52) and (53) state that the starting time of heating and cooling in the current time interval should be equal to the finishing time at the previous time interval.

$$tuu(s_{inj_h}, p, pp) = tpp(s_{inj_h}, p, pp - 1), \quad \forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h} \tag{52}$$

$$tuu(s_{inj_c}, p, pp) = tpp(s_{inj_c}, p, pp - 1), \quad \forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c} \tag{53}$$

Constraints (54) state that the starting time of the heat storage unit at the current time interval should be equal to the finishing time at the previous time interval.

$$tuu(u, p, pp) = tpp(u, p, pp - 1), \quad \forall p, pp \in P,\ u \in U \tag{54}$$

Constraint (55) states that the finishing time of a heat storage unit in a time interval should be equal to or greater than the starting time of the same time interval.

$$tpp(u, p, pp) \geq tuu(u, p, pp), \quad \forall p, pp \in P,\ u \in U \tag{55}$$

Constraint (56) states that the starting time of the heat storage unit at time point p should be greater than or equal to the finishing time at the previous time point $p-1$.

$$tuu(u, p, pp = p) = tpp(u, p-1, pp = p-1+n), \quad \forall p, pp \in P,\ u \in U \tag{56}$$

Constraints (57) and (58) state that if the binary variable associated with heat integration is active, then the binary variable associated with heating and cooling must be active.

$$x(s_{inj_c}, s_{inj_h}, p, pp) \leq v(s_{inj_h}, p, pp), \quad \forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \tag{57}$$

$$x(s_{inj_c}, s_{inj_h}, p, pp) \leq v(s_{inj_c}, p, pp),$$
$$\forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (58)$$

Constraints (59) and (60) state that the heating and cooling loads take on a value for a certain duration when the binary variables associated with heating and cooling are active.

$$tpp(s_{inj_h}, p, pp) - tuu(s_{inj_h}, p, pp) \leq H * v(s_{inj_h}, p, pp),$$
$$\forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h} \quad (59)$$

$$tpp(s_{inj_c}, p, pp) - tuu(s_{inj_c}, p, pp) \leq H * v(s_{inj_c}, p, pp),$$
$$\forall p, pp \in P,\ s_{inj_c} \in S_{inJ_c} \quad (60)$$

Constraint (61) states that the cooling of a hot unit will be satisfied by direct heat integration, indirect heat integration or external cooling utility if required.

$$cl(s_{inj_h}, p) = cw(s_{inj_h}, p) + \sum_{s_{inj_c}} \sum_{pp=p}^{pp=p+n} Qe(s_{inj_h}, s_{inj_c}, p, pp) + \sum_{pp=p}^{pp=p+n} Q(s_{inj_h}, u, p, pp),$$
$$\forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (61)$$

Constraint (62) states that the heating of a cold unit will be satisfied by direct heat integration, indirect heat integration or external heating utility if required.

$$hl(s_{inj_c}, p) = st(s_{inj_c}, p) + \sum_{s_{inj_h}} \sum_{pp=p}^{pp=p+n} Qe(s_{inj_h}, s_{inj_c}, p, pp) + \sum_{pp=p}^{pp=p+n} Q(s_{inj_c}, u, p, pp),$$
$$\forall p, pp \in P,\ s_{inj_h} \in S_{inJ_h},\ s_{inj_c} \in S_{inJ_c} \quad (62)$$

3.2. Model objective functions

Equation (63) is the objective function in terms of profit maximization, with profit defined as the difference between revenue from product and cost of utility.

$$\max(\sum_{s^p} price(s^p) qs(s^p) - \sum_p \sum_{s_{inj_h}} costc * cw(s_{inj_h}, p) - \sum_p \sum_{s_{inj_c}} costst * st(s_{inj_c}, p)),$$
$$\forall p, pp \in P, s_{inj_h} \in S_{inJ_h}, s_{inj_c} \in S_{inJ_c}, s_{inj} \in S_{inJ} \quad (63)$$

Equation (64) defines the minimization of utility if the product demand is known.

$$\min(\sum_p \sum_{s_{inj_h}} costcw * cw(s_{inj_h}, p) + \sum_p \sum_{s_{inj_c}} costst * st(s_{inj_c}, p)),$$
$$\forall p, pp \in P, s_{inj_h} \in S_{inJ_h}, s_{inj_c} \in S_{inJ_c}, s_{inj} \in S_{inJ} \quad (64)$$

4. Case studies

In order to demonstrate the application of the proposed model, three literature case studies are presented. The results in all the case studies for the proposed model were obtained using a Pentium 4 with 3.2 GHz processor and 512 MB RAM. CPLEX and CONOPT 2 in GAMS 22.0 were used to solve the MILP and NLP problems, respectively. DICOPT 2 was used as the interface for solving the MINLP problem. The computational results of this work are compared with results from the literature.

4.1. Case I

This case study, obtained from Kondili et al. [44], has become one of the most commonly used examples in literature. However, this case study has been adapted by Halim and Srininvasan [20] to include energy integration. The batch plant produces two different products sharing the same processing units, where Figure 3 shows the plant flowsheet. The unit operations consist of preheating, three different reactions and separation. The plant accommodates many common features of multipurpose batch plants such as units performing multiple tasks, multiple units suitable for a task and dedicated units for specific tasks. The STN and state sequence network (SSN) representations of the flowsheet are shown in Figure 4. The production recipe is as follows.

(i) Raw material, Feed A, is heated from 50°C to 70°C to form HotA used in reaction 2.

(ii) Reactant materials, 50% Feed B and 50% Feed C are used in reaction 1 to produce IntBC. During the reaction the material has to be cooled from 100°C to 70°C.

(iii) 60% of the intermediate material, IntBC, and 40% of HotA are used in reaction 2 to produce product 1 and IntAB. The process needs to be heated from 70°C to 100°C during its operation.

(iv) 20% Feed C, and 80% of intermediate, IntAB, from reaction 2 are used in reaction 3 to produce ImpureE. The reaction needs its temperature to be raised from 100°C to 130°C during its operation.

(v) The separation process produces 90% product 2 and 10% IntAB from Impure E. Cooling water is used to lower its temperature from 130°C to 100°C.

The processing time of a task i in unit j is assumed to be linearly dependent, $\alpha i + \beta i B$ on its batch size B. Where αi is a constant term of the processing time of task i and βi is a coefficient of variable processing time of task i. The batch dependent processing time makes this case study more complex. Table 1 gives the relevant data on coefficients of processing times, the capacity of the processing units, initial inventory of raw materials, storage capacity and relevant costs. The production demand is given as 200 kg for both Prod1 and Prod2. Table 2 gives data pertaining to heat integration. The objective here is optimization with respect to makespan and energy.

4.1.1. Results and discussion

The computational results obtained using the proposed model as well as those of Halim and Srinivasan [20] are presented in Table 3. The model of Stamp and Majozi [1]

Table 1: Scheduling data for case study I.

Task(i)	Unit(j)	Max batch size(kg)	α (s_{inj})	β (s_{inj})	Material state (s)	Initial inventory	Max storage (kg)	Revenue or cost ($/kg or $/MJ)
Heating (H)	HR	100	0.667	0.007	Feed A	1000	1000	0
Reaction 1 (R1)	RR1	50	1.334	0.027	Feed B	1000	1000	0
	RR2	80	1.334	0.017	Feed C	1000	1000	0
Reaction 2 (R2)	RR1	50	1.334	0.027	HotA	0	100	0
	RR2	80	1.334	0.017	IntAB	0	200	0
Reaction 3 (R3)	RR1	50	0.667	0.013	IntBC	0	150	0
	RR2	80	0.667	0.008	ImpureE	0	200	0
Separation (S)	SR	200	1.334	0.007	Prod1	0	1000	20
					Prod2	0	1000	20
					Cooling water			0.02
					Steam			1

Table 2: Data required for energy integration for Case I.

Task(i)	T^{in}(°C)	T^{out}(°C)	Unit(j)	C$_p$(kJ/kg°C)
Heating(H)	50	70	HR	2.5
Reaction 1	100	70	RR1	3.5
			RR2	3.5
Reaction 2	70	100	RR1	3.2
			RR2	3.2
Reaction 3	100	130	RR1	2.6
			RR2	2.6
Separation	130	100	SR	2.8
Cooling water	20	30		
Steam	170	160		

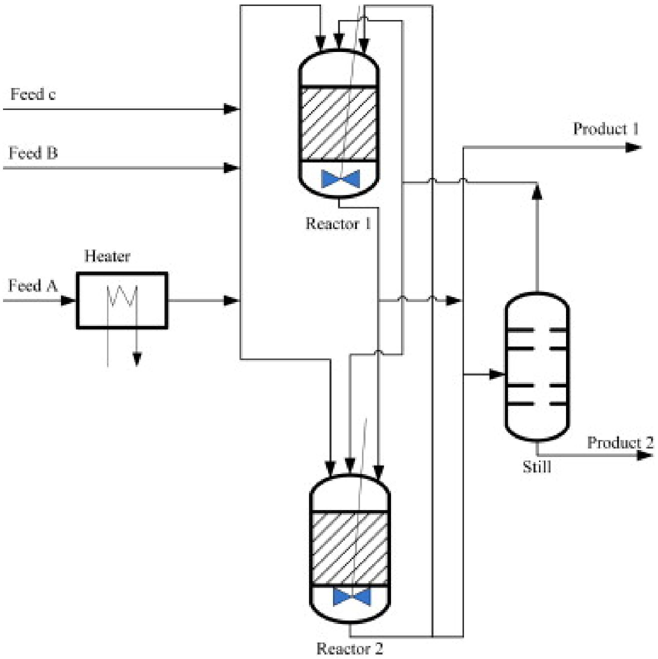


Figure 3: Flowsheet for case study I.

is not included in the comparison since the model does not cater for temperature variation during processing of tasks. The minimum temperature driving force for heat exchange is assumed 10°C. For makespan minimization, an objective value of 19.5 h was obtained using the proposed model, which is much better than 19.96 h obtained by Halim and Srinivasan [20] as a result of using the recent robust scheduling model. Using the makespan obtained, the case study was solved to minimize the energy demand by setting customer requirement for Product 1 and Product 2. The total energy required for the standalone operation was 125.5 MJ.

By using energy integration the total energy requirement was reduced from 125.5 MJ in standalone operation to 51.4 MJ (38.7 MJ hot utility and 12.8 MJ cold utility), resulting in a 59% energy saving. The performance of the proposed model was also compared to the technique by Halim and Srinivasan [20]. They solved this case study based on a three step sequential framework. First, the schedule is optimized to meet the economic objective of makespan minimization. Next, alternate schedules are generated through a stochastic search-based integer cut procedure. Finally, the heat integration model is solved for each of the resulting schedules to establish the minimum utility targets. In generating alternate optimal solutions, they used integer cut variables to 6; that is in each iteration six tasks were pre-assigned to different units at different slots. After 1000 MILP iteration of stochastic search, three sets of solutions at three different makespans (20.03, 20.02, 19.96) where obtained. Based on this set of schedules, the heat integration model was solved. The makespan that gave the minimum utility target was 19.96 with the corresponding utility requirement of 40.8 MJ hot utility and 15.6 MJ cold utility. Figure 5 shows the optimization results after 1000

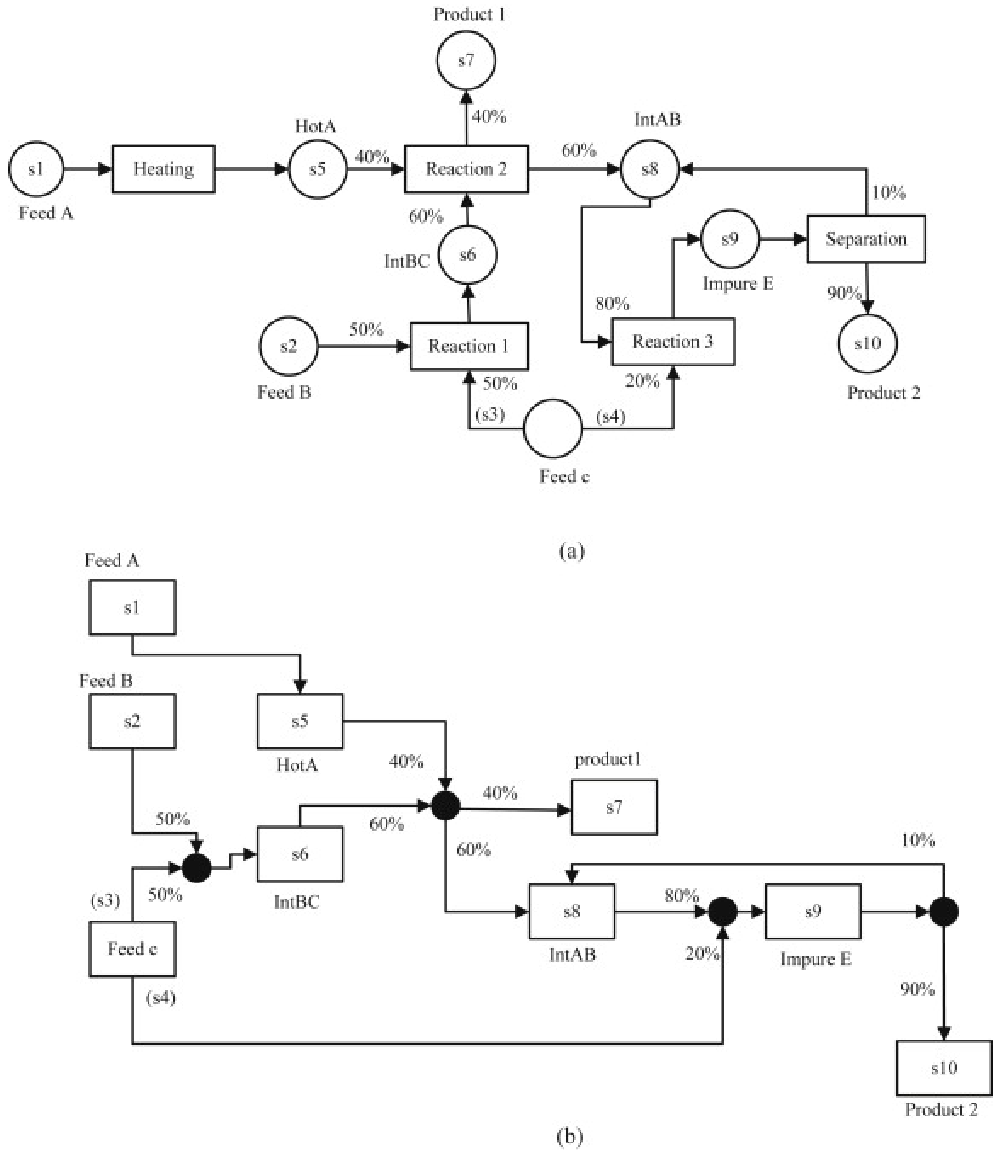


Figure 4: STN (a) and (b) SSN representation for case study I.

iteration of the stochastic search.

The developed model gives a better makespan and a further utility saving of 8.8% compared to the results of Halim and Srinivasan [20]. An additional feature of the proposed model is its efficient solution technique. The optimal solution was found after solving only one MINLP model which was solved in a reasonable specified CPU time of 2 h. The authors Halim and Srinivasan [20] did not report the CPU time required to solve this problem. We believe that it is computationally expensive because of the need to generate alternate optimal schedules.

Figure 6 details the amount of heat exchanged between the cold and hot units and the time intervals during which energy integration occurs.

The energy requirements of units RR1,

Table 3: Computational results for case study I.

	Proposed formulation without energy integration	Proposed formulation with energy integration	Halim and Srinivasan [20] with energy integration
Objective($)	125.5	51.4	56.4
Steam(MJ)	75.2	38.7	40.8
Cooling water(MJ)	50.2	13.5	15.6
Revenue from product($)	4000	4000	4000
Number of time points/slots	8	8	N/A
Number of binary variables	92	500	N/A
CPU time(h)	0.39	2	N/A

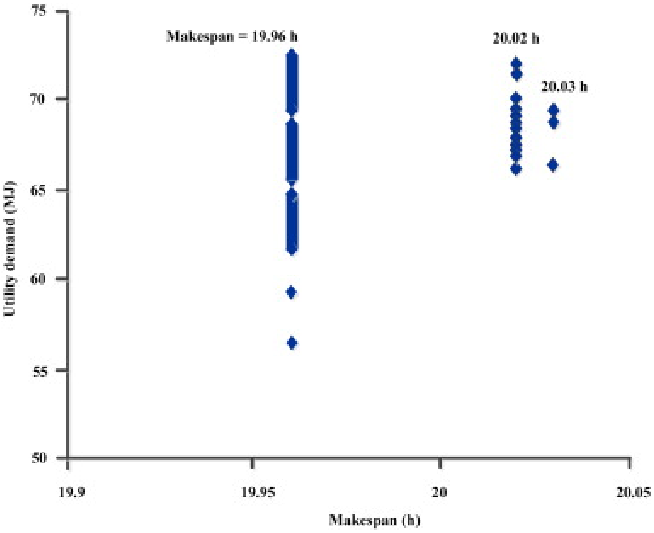


Figure 5: Optimization results using stochastic search-based integer cut procedure by Halim and Srinivasan [20].

RR2 and HR during the interval 4.976 h to 7.660 h are explained to highlight the advantage of the proposed model. The heating load of unit RR2 between 4.976 h and 6.660 h is 4.658 MJ. This is partly satisfied through energy integration with unit RR1 in the same time interval, resulting in an external heating requirement of 1.364 MJ rather than 4.658 MJ if it operated in standalone mode. The heating requirement for RR2 between 6.660 h and 7.591 h is fully satisfied with external steam (2.575 MJ) since it is not in the heat integrated mode. The cooling requirement of RR1 between 4.976 h and 6.660 h is 3.294 MJ. This heating requirement is satisfied by heat integration with unit RR2. For the time interval between 6.660 h and 7.660 h the cooling requirement for RR1 is 1.956 MJ that can be fully satisfied with matching to unit HR. This demonstrates the advantage of the developed model where it allows unit RR1 to

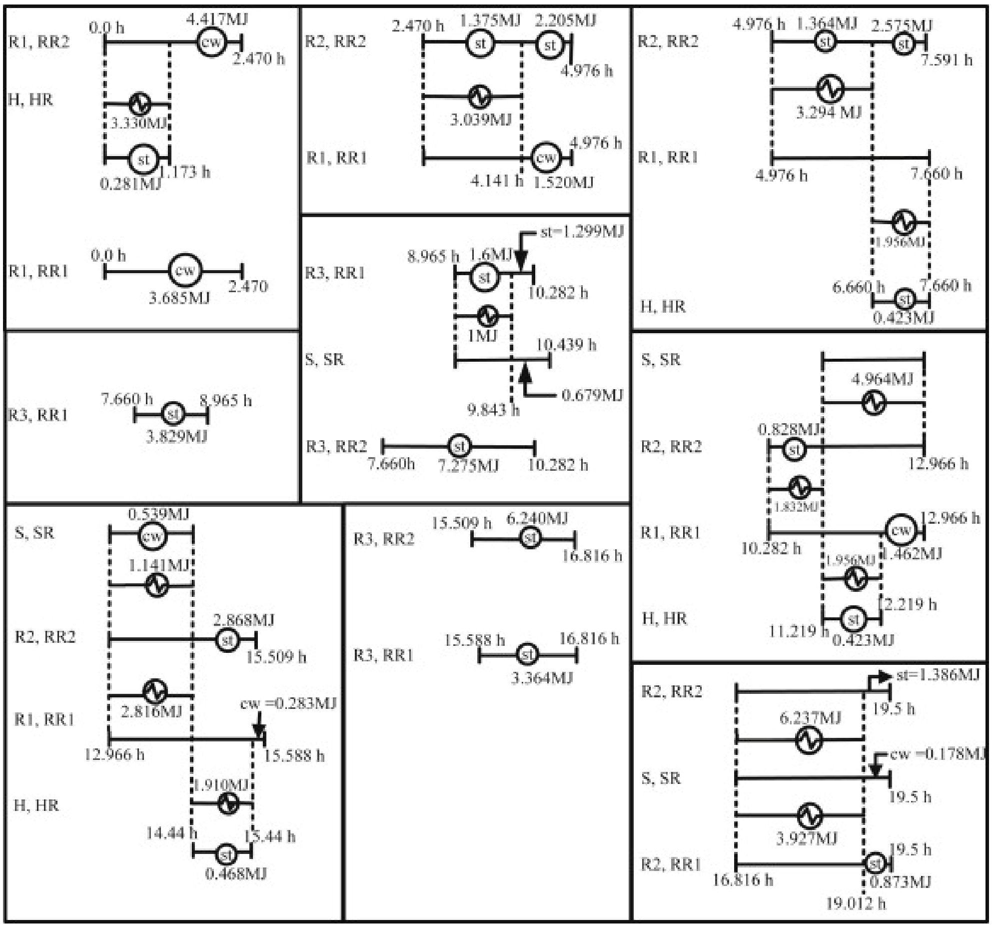


Figure 6: Heat exchange network for Case I using the proposed model.

be heat integrated with multiple units at different time intervals for better heat recovery. Literature models based on simultaneous approach allow a unit to be heat integrated with other units only for one time interval during its operation. Figure 7 shows the Gantt chart related to the optimal usage of resources. It also indicates the types of tasks performed in each piece of equipment, and the starting and finishing times of the processing tasks.

4.2. Case II

This example, which was first examined by Sundaramoorthy and Karimi [45], is studied extensively in literature. It is a relatively complex problem and is often used in literature to check the efficiency of models in terms of optimal objective value and CPU time required. The plant has many common features of a multipurpose batch plant, with the following features: units performing multiple tasks, multiple units suitable for a task, states shared by multiple tasks and different products produced following different production paths. The state task network and state sequence network representations for this case study are depicted in Figure 8. The scheduling data are modified to incorporate heat integration opportunities and are presented in Table 4 and Table 5. Data necessary for heat inte-

Table 4: Scheduling data for Case II.

Unit	Capacity	Suitability	Mean processing time(h)
Heater	100	H1,H2	1,1.5
Reactor 1	100	RX1,RX2,RX3	2,1,2
Reactor 2	150	RX1,RX2,RX3	2,1,2
Separator	300	Separation	3
Mixer 1	200	Mixing	2
Mixer 2	200	Mixing	2

Table 5: Scheduling data for Case II.

State	Description	Storage capacity(ton)	Initial amount(ton)	Revenue(c.u/ton)
S1	Feed 1	Unlimited	Unlimited	0
S2	Feed 2	Unlimited	Unlimited	0
S3	Int 1	100	0	0
S4	Int 2	100	0	0
S5	Int 3	300	0	0
S6	Int 4	150	50	0
S7	Int 5	150	50	0
S8	Feed 3	Unlimited	Unlimited	0
S9	Int 6	150	0	0
S10	Int 7	150	0	0
S11	Feed 4	Unlimited	Unlimited	0
S12	Product 1	Unlimited	0	1000
S13	Product 2	Unlimited	0	1000
Parameters				Values
Specific heat capacity for heat storage c_p (kJ/kg°C)				4.2
Steam cost (c.u/kWh)				10
Cooling water cost (c.u/kWh)				2
$\triangle T^{min}$(°C)				10
T^L (°C)				20
T^U (°C)				180
W^L (ton)				1
W^U (ton)				3

Table 6: Heating/cooling requirements for Case II.

Reaction	Type	Heating/cooling requirement(kWh)	Operating temperature (°C)
Fixed batch size			
RX1	Exothermic	60 (cooling)	100
RX2	Endothermic	80 (heating)	60
RX3	Exothermic	70 (cooling)	140

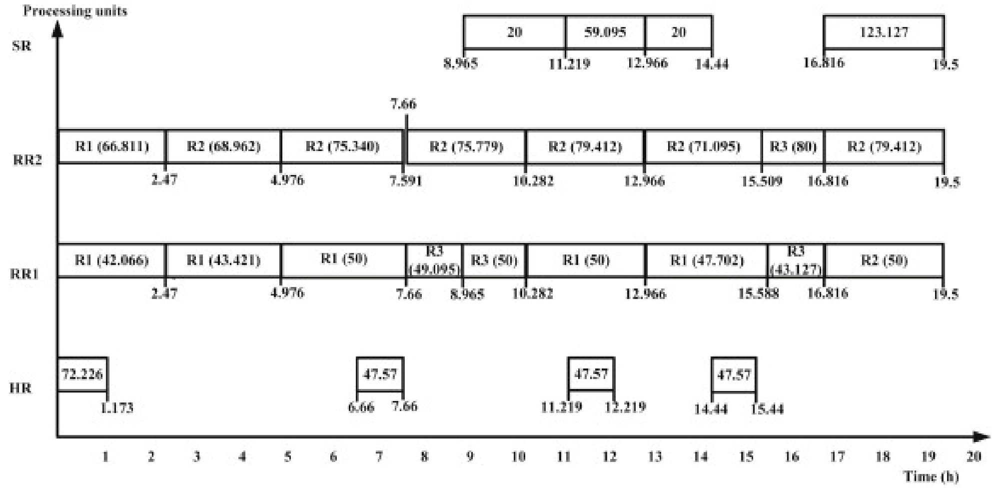


Figure 7: Gantt chart for Case I using the proposed model.

gration are presented in Table 6.

4.2.1. Results and discussions

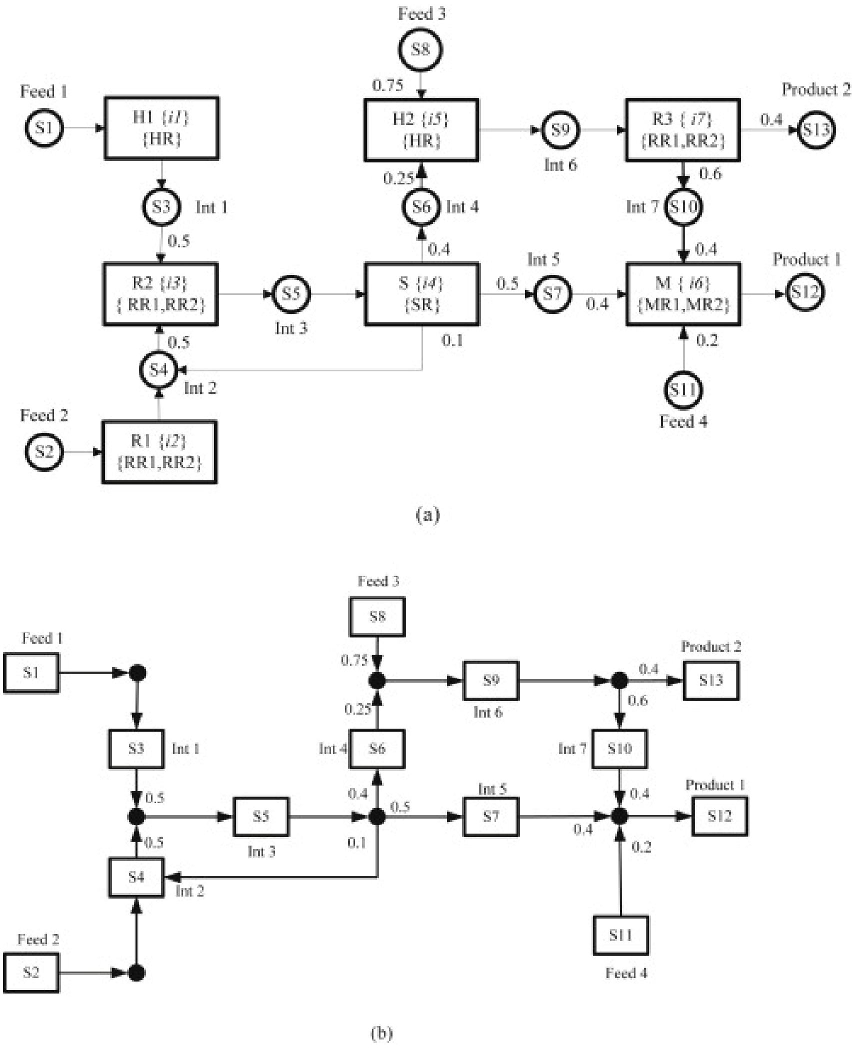
The computational results obtained from the different models for this case study are presented in Table 7. This case study evaluates the efficiency of the proposed model for indirect heat integration. The recent more advanced sequential methodology for energy integration by Halim and Srinivasan [20] do not included in the comparison since their model do not consider the use of heat storage for indirect heat integration.

For indirect heat integration, using a time horizon of 10 h, the proposed model and the model by Stamp and Majozi [1] give the same optimal objective value of $224,000$,while the proposed model gives a better CPU time. It is interesting to note that by having heat storage, the utility requirement is reduced to 0.0 signifying that operating a heat integrated batch plant with heat storage provide great chance for heat recovery. For a time horizon of 12 h, the model by Stamp and Majozi [1] required more than two days to solve, while the proposed model significantly reduced the required CPU time (35.2 s for the proposed model vs. 238,640 s for Stamp and Majozi [1]). The reduction in CPU time results from reduced number of time points required (7 for the proposed model vs. 11 for Stamp and Majozi [1]). However, the proposed model required a higher number of binary variables. This is due to catering for proper sequencing of tasks for the FIS policy which was inadvertently violated by the scheduling model used by Stamp and Majozi [1] and is explained well in the next case study. A better optimal objective value of 287,965 was obtained by the proposed model as compared to 287,640 by Stamp and Majozi [1]. This indicates that the use of efficient scheduling techniques as a platform for a heat integration model improves the computational efficiency, both in terms of CPU time and optimal objective value for heat integration in multipurpose batch plants.

The amount of material processed, the starting and finishing times, the amount of heat exchanged between units and heat storage and the utility requirements of the units for a time horizon of 12 h for indirect

Table 7: Computational results for Case II, fixed batch size with units operating at 80% capacity.

	Standalone operation, Stamp and Majozi [1]	Standalone operation, proposed	Indirect heat integration, Stamp and Majozi [1]	Indirect heat integration, proposed
H = 10				
Performance index (cost units)	222,000	222,000	224,000	224,000
External cold duty (kWh)	200	200	0	0
External hot duty (kWh)	160	160	0	0
Heat storage capacity (ton)			1.905	1.905
Initial heat storage temperature (°C)			82.5	82.5
CPU time(s)	5.3	1	68	7.8
Binary variables	66	101	156	209
Time points	7	6	7	6
H = 10				
Performance index (cost units)	285,860	285,860	287,640	287,9650
External cold duty (kWh)	270	270	130	17.5
External hot duty (kWh)	160	160	10	0
Heat storage capacity (ton)			5	1.905
Initial heat storage temperature (°C)			87.143	82.5
CPU time(s)	7.7	1.9	238,896	35.2
Binary variables	99	155	206	246
Time points	9	7	11	7



(a)

(b)

Figure 8: (a) STN representation and (b) SSN representation for Case II.

heat integration is given in Figure 9. The numbers in the boxes represents the amount of batch processed in the unit.

4.3. Case III

This case study was taken from the petrochemical plant by Kallrath [46] and used as a benchmark problem in the scheduling environment for multipurpose batch plants. We adapted this case study to incorporate energy integration. The recipe representation for the plant is presented in Figure 10. It is a very complex problem where 10 reactors, 15 storage units and 18 states are considered. There are reactors dedicated to a specific task, while there are also reactors conducting multiple tasks, some capable of executing up to 5 different tasks. The mixed intermediate storage (MIS) policy is assumed in this case study. Scheduling data is given in Table 8. The plant is required to satisfy demand requirement of 50 ton for S14, S17 and S18; 100 for S15 and 400 for S16 within a time horizon of 120 h. The heating and cooling requirements for each task are given in Table 9.

Table 8: Scheduling data required for Case III.

Unit	Suitability	Capacity(ton)	Revenue(10^3c.u/ton)
R 1	Task T1	0:100	
R 2	Task T2	0:100	
R 3	Task T3	0:100	
R 4	Task T4,T5,T6,T7	0:100	
R 5	Task T8,T9	0:150	
R 6	Task T10,T11,T12	0:50	
R 7	Task T10,T11,T12	0:50	
R 8	Task T13,T14,T15,T16,T17	0:100	
R 9	Task T13,T14,T16,T17	0:100	
R 10	Task T8	0:100	
V0	Store S0	0:1000	0
V1	Store S1	0:100	0
V2	Store S2	0:100	0
V3	Store S3	0:100	0
V4	Store S4	0:100	0
V6	Store S6	0:100	0
V7	Store S7	0:100	0
V8	Store S8	0:100	0
V11	Store S11	0:100	0
V13	Store S13	0:100	0
V5,V9,V10,V12	V5 for S5, V9 for S9, V10 for S10, V12 for S12	0:0	0
V14	Store S14	0:1000	5
V15	Store S15	0:1000	5
V16	Store S16	0:1000	10
V17	Store S17	0:1000	7.5
V18	Store S18	0:1000	7.5

Table 9: Heating/cooling requirement for Case III.

Task	Heating/cooling requirement(MWh)	Operating temperature(°C)	Cost(c.u/MWh)
T1	$40 + 0.2\beta$ heating	150	
T2	$70 + 0.15\beta$ cooling	200	
T3	$50 + 0.3\beta$ cooling	230	
T4	$50 + 0.3\beta$ heating	120	
T5	$55 + 0.25\beta$ heating	120	
T6	$60 + 0.6\beta$ heating	120	
T7	$45 + 0.45\beta$ heating	120	
Steam		270	1
Cooling water		30	0.2

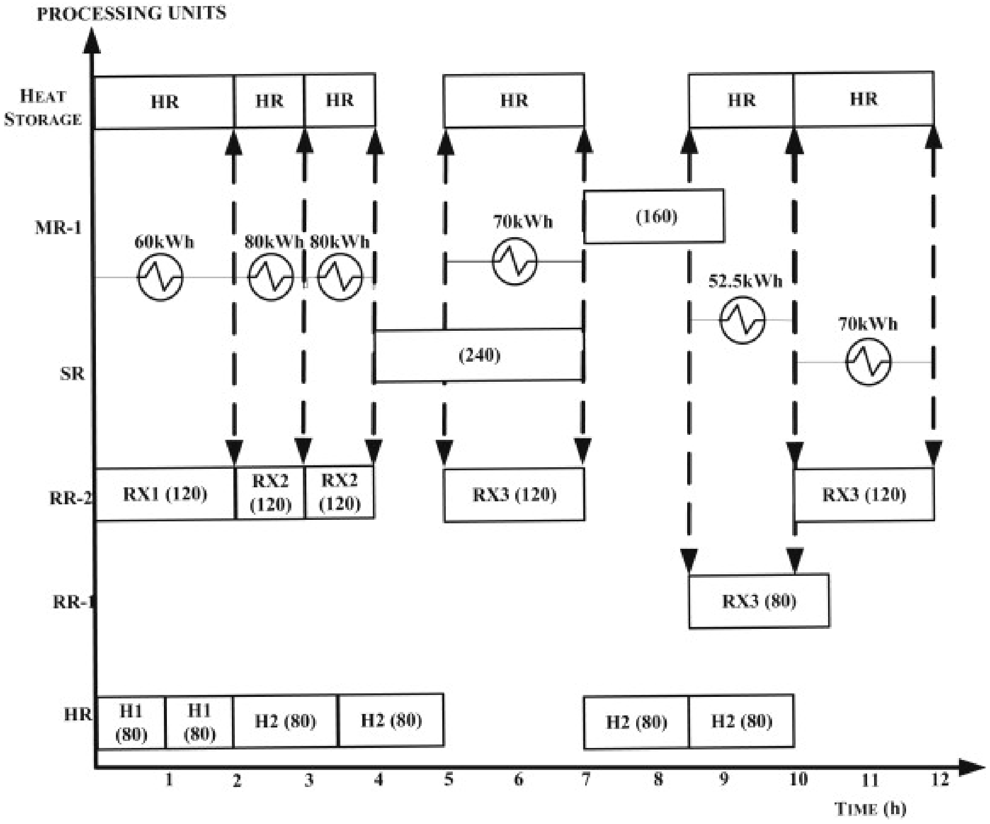


Figure 9: Gantt chart for indirect heat integration, proposed model.

4.3.1. Results and discussions

The computational statistics obtained for this case study are presented in Table 10. For the standalone operation using the technique of Stamp and Majozi [1] where based on the scheduling techniques of Majozi and Zhu [33], the model gives an objective value of 6.74×10^6c.u. The model required 17 time points and 425 binary variables and was solved in a specified CPU time of 5000 s. By implementing the proposed model on the same computer an objective value of 6.5899×10^6c.u was obtained. This model required 550 binary variables and was solved in a specified CPU time of 5000 s.

It would be expected that the proposed model should give the same or a better objective value, since the model uses a more robust scheduling technique as a platform. However, the slightly inferior result obtained is due to the need to catering for proper sequencing for the FIS policy. This is better described by the Gantt chart depicted in Figure 11. The maximum storage capacity for state S1 is 100 ton, but this limit is violated a number of times during the time horizon using the model of Stamp and Majozi [1]. The numbers inside the boxes in Figure 11 represents the amount of batch processed. It is clear from this figure that the state S1 produced from reactor R1 is consumed in reactor R2 in consecutive time points. For example the state S1 consumed in reactor 1 at time points P1, P2 and P3 is consumed in reactor 2 at time points P2, P3 and P4, respectively. These

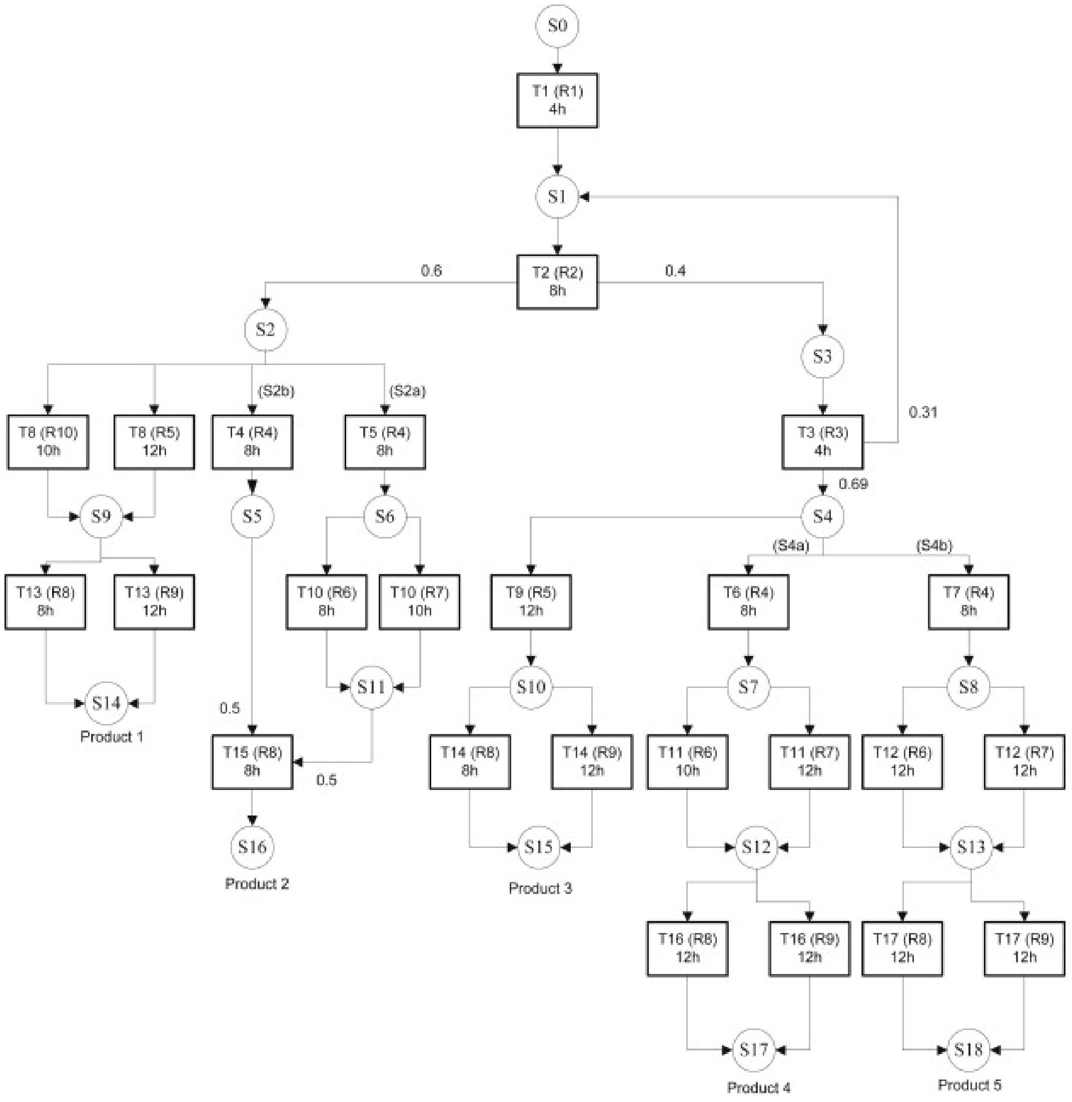


Figure 10: Recipe representation for Case III.

indicate that the amount of material produced is consumed immediately in the next time point so that the storage constraint is not violated. However, in real time the storage capacity is violated because of inadequate sequencing constraints that improperly match the consuming task, the producing task and storage. The same explanation holds for state S5 where there is no storage available to store state S5. However, from Figure 11 it can be seen that this constraint is violated in real time and 50-ton storage is actually required. This inadvertent violation of FIS storage policy is resolved using the proposed model and the right Gantt chart for this case study is presented in Figure 12.

Using the proposed model for direct heat integration an objective value of 7.9107×10^6c.u was obtained, which is much better than the standalone operation, corresponding to a 20% improvement in profit. The

Table 10: Computational results for Case III.

	Standalone operation using Stamp and Majozi [1]	Standalone operation using proposed model	Proposed model with di energy integration
Objective value(10^3c.u)	6740	6589.9	7910.7
Product 1(ton)	100	100	90
Product 2(ton)	600	600	600
Product 3(ton)	103.6	165.6	120.8
Product 4(ton)	100	50	55.2
Product 5(ton)	100	88	100
Cooling water(MJ)	1447	1600	276.75
Steam(MJ)	1488.53	1453	251.95
Binary variable	425	550	1315
CPU time(s)	5000	5000	6008

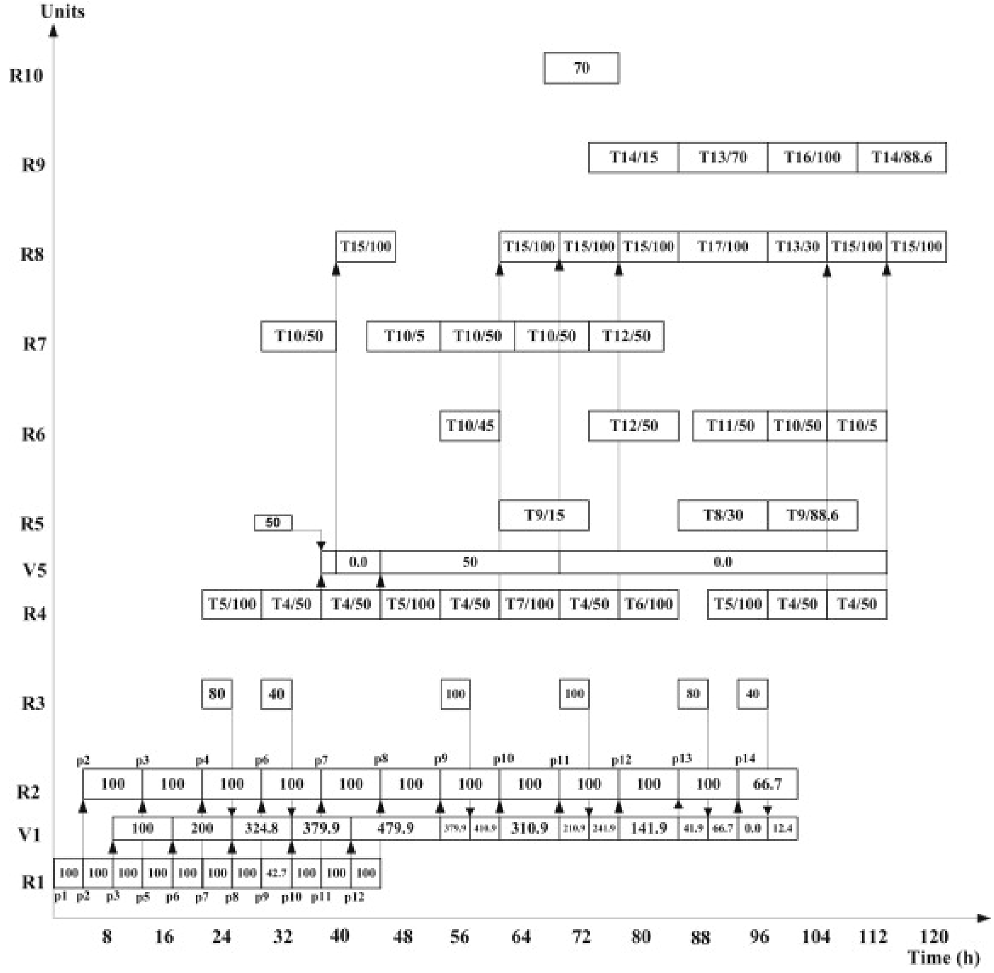


Figure 11: Gantt chart for Case III using Stamp and Majozi [1] for standalone operation.

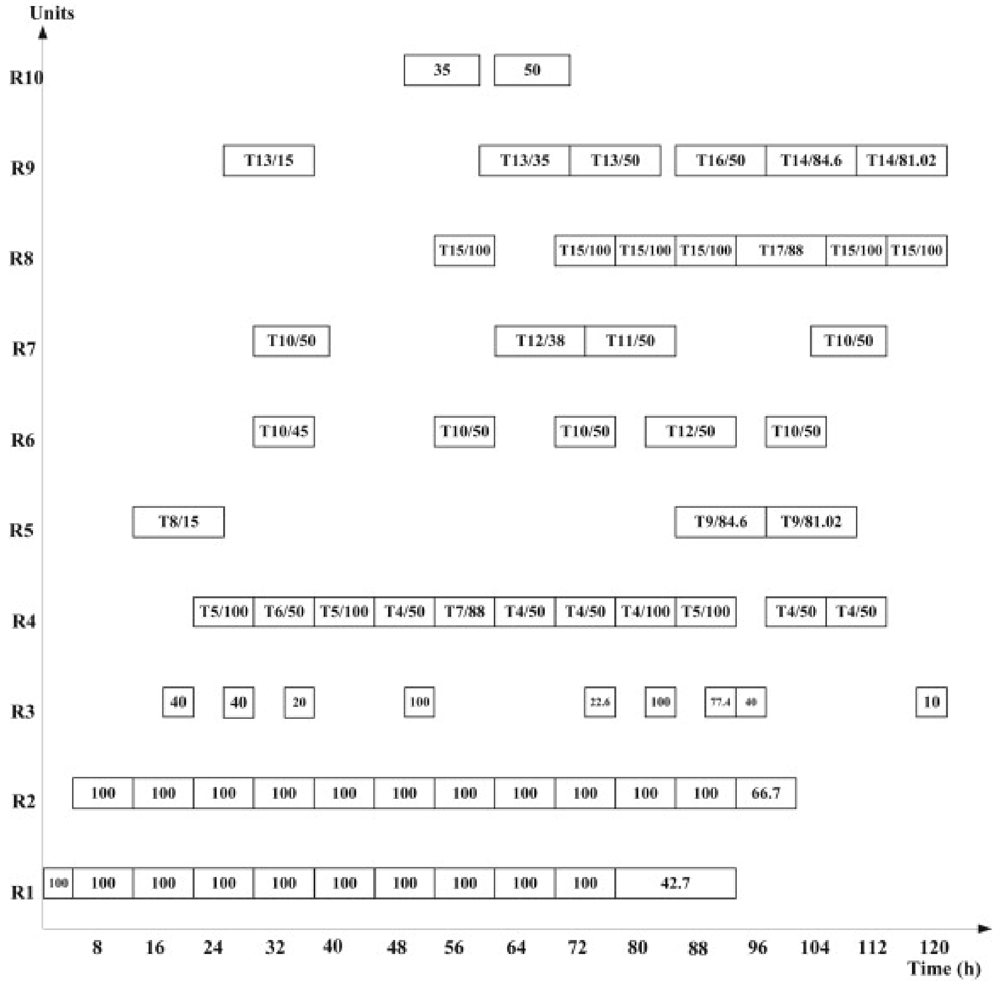


Figure 12: Gantt chart for Case III using the proposed model for standalone operation.

utility reduction is also compared, for the energy integrated mode 528.7 MJ of utility is required which is much better than the utility requirement of 3053 MJ for standalone operation. This corresponds to an 82.7% utility reduction when the tasks are operated in energy integrated mode. The model required 16 time points, $n = 2$ and 1315 binary variables and was solved in less than 2 h using specified CPU time of 2000 s for the MILP subproblem. The energy integration network for the time horizon of 120 h is depicted in Figure 13.

The energy integration in the interval between 12 h and 20 h is elaborated on for better understanding. The cooling water requirement for Task 2 is 10.625 MW (heat load/duration of the task, 85 MJ/8 h). During the time interval of 12 h to 16 h, Task 2 is integrated with the cold task 5 and exchange a heat load of 33.75 MJ. The cooling requirement for Task 2 in this time interval is 42.5 MJ obtained by multiplying the energy requirement per hour with the duration of the heat exchange (10.625 MW*4 = 42.5). The deficit cooling requirement for Task 2, which is (42.5 MJ 33.75 MJ = 8.75 MJ), is satisfied with external cooling. The

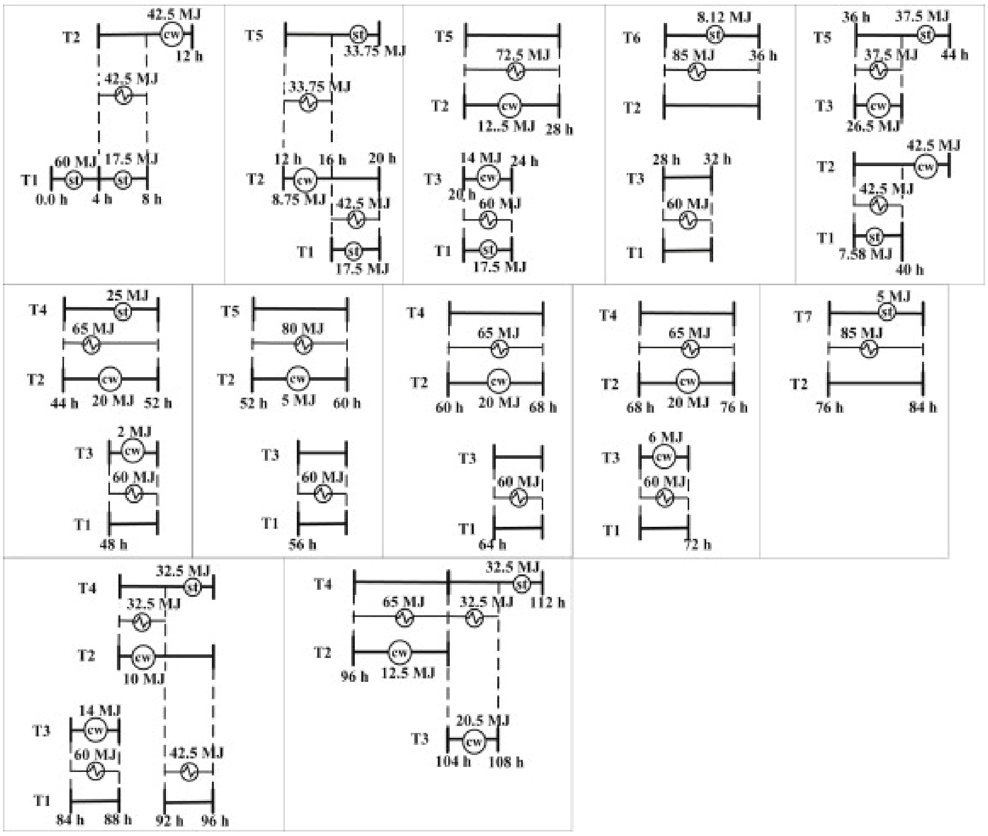


Figure 13: Heat exchange network for Case III for the time horizon of 120 h.

heating requirement for Task 5 in this interval is fully satisfied with heat integration of Task 2. The cooling requirement for Task 2 during the interval between 16 h and 20 h is fully satisfied with energy integration of Task 1. The heating requirement for Task 1 during this interval is 60 MJ and satisfied partially with the energy integration of Task 2 and the rest which is 17.5 MJ from external heating. The heating requirement for Task 5, which is 33.5 MJ during the interval between 16 h and 20 h, is satisfied fully with external heating since it is not in the energy integrated mode. The same principle is applied to calculate and satisfy the energy requirement for each hot and cold task for the entire time horizon. The Gantt chart that shows the amount of batch processed, the type of task performed in a unit, and the starting and finishing times for the energy integrated mode for this case is presented in Figure 14.

5. Conclusions

An efficient continuous time mathematical model for direct and indirect heat integration is presented. Most heat integration models rely on a predefined schedule, which leads to suboptimal results. This paper incorporates heat integration into the scheduling framework and solved simultaneously. The model is capable of solving for both direct and indirect heat integration. By using a heat storage vessel, a considerable reduction in utility consumption is achieved. When this work is compared to

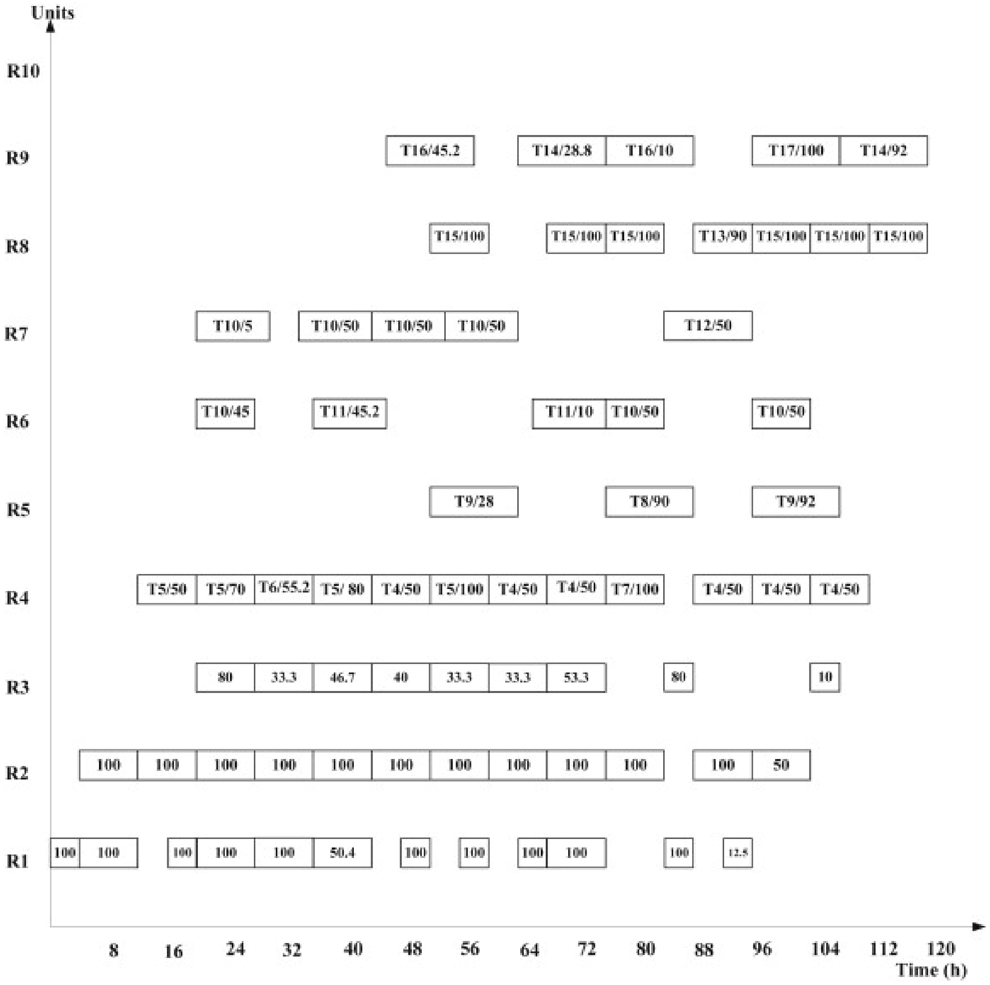


Figure 14: Gantt chart for Case III using direct heat integration.

recent existing work, the formulation performs better in terms of both optimal objective value and CPU time. Future communication will address extending the developed model to incorporate capital cost of heat exchanger.

Nomenclature

Sets

S_{inJ_h}	$\{s_{inj_h} \mid s_{inj_h}$ task which needs cooling$\}$
S_{inJ_c}	$\{s_{inj_c} \mid s_{inj_c}$ task which needs heating$\}$
S_{inJ}	$\{s_{inj} \mid s_{inj}$ any task$\}$
P	$\{p \mid p$ time point$\}$
U	$\{u \mid u$ is a heat storage unit$\}$

Parameters

$cp(s_{inj_h})$	specific heat capacity for the heating task
$cp(s_{inj_c})$	specific heat capacity for the cooling task
$cp(u)$	specific heat capacity for the heat storage
$T^{in}_{s_{inj_h}}$	inlet temperature of the heating task
$T^{out}_{s_{inj_h}}$	outlet temperature of the heating task
$T^{in}_{s_{inj_c}}$	inlet temperature of the

	cooling task
$T^{out}_{s_{inj_c}}$	outlet temperature of the cooling task
$\triangle T^U$	maximum thermal driving force
$\triangle T$	minimum thermal driving force
M	big-M mostly equivalent to the time horizon
Q^U	maximum heat requirement from the heating and cooling task
$price(s^p)$	price of a product
$costst$	cost of steam
$costcw$	cost of cooling water
H	time horizon of interest
	Variables
$x(s_{inj_c}, s_{inj_h}, p, pp)$	binary variable signifying whether heat integration occurs between the hot and cold unit
$y(s_{inj_h}, p)$	binary variable associated to whether the hot state is active at time point p or not
$y(s_{inj_c}, p)$	binary variable associated to whether the cold state is active at time point p or not
$v(s_{inj}, p, pp)$	binary variable associated to whether the hot and cold states are active at time point p and extended time point pp
$cl(s_{inj_h}, p)$	cooling load required by the hot task at time point p
$hl(s_{inj_c}, p)$	heating load required by the cold task at time point p
$avcl(s_{inj_h}, p)$	average cooling load required by the hot task at time point p using time average model
$avhl(s_{inj_c}, p)$	average heating load required by the cold task at time point p using time average model
$mu(s_{inj_h}, p)$	amount of material processed by the hot task
$mu(s_{inj_c}, p)$	amount of material processed by the cold task
$qs(s^p)$	amount of product produced at the end of the time horizon.
$tp(s_{inj}, p)$	finishing time of a task
$tu(s_{inj}, p)$	starting time of a task
$clp(s_{inj_h}, p, pp)$	cooling load required by the hot task active at time point p and extended time point pp
$hlp(s_{inj_c}, p, pp)$	heating load required by the cold task active at time point p and extended time point pp
$tuu(s_{inj}, p, pp)$	starting time of a task active at time point p and extended time point pp
$tpp(s_{inj}, p, pp)$	finishing time of a task active at time

	point p and extended time point pp
$tuu(u, p, pp)$	starting time of a heat storage at time point p and extended time point pp
$tpp(s_{inj}, p, pp)$	finishing time of a heat storage at time point p and extended time point pp
$T^{in}(s_{inj}, p, pp)$	inlet temperature of a task active at time point p and extended time point pp
$T^{out}(s_{inj}, p, pp)$	outlet temperature of a task active at time point p and extended time point pp
$T_0(u, p, pp)$	inlet temperature of a heat storage active at time point p and extended time point pp
$T_f(u, p, pp)$	outlet temperature of a heat storage active at time point p and extended time point pp
$Qe(s_{inj_c}, s_{inj_h}, p, pp)$	amount of heat load exchanged by the hot and cold unit active at time point p and extended time point pp
$Q(s_{inj}, u, p, pp)$	amount of heat load exchanged between a task and heat storage
$cw(s_{inj_h}, p)$	external cooling water used by the hot task
$st(s_{inj_c}, p)$	external heating used by the cold task
$W(u)$	capacity of heat storage unit

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