Optimal design of multipurpose batch facilities with direct, indirect and solar heat integration

Pedro Simão

Department of Engineering and Management, Instituto Superior Técnico

Abstract

Sustainability is currently one of the main trends among consumers and companies. With the increasing price of fossil fuels the opportunity to leverage renewable technologies keeps getting higher, as they are getting more efficient, more reliable and less costly.

Therefore, based on the previous work of Pinto et al. (2003) a discrete MILP model is presented, where solar thermal and heat storage technologies are included with both variable heat volume and number of solar collectors, with the aim of profit maximization, providing a valuable information for decision-making process.

Keywords: Multipurpose batch facilities; Heat integration; Solar thermal energy; Energy storage; Design optimization; Scheduling; Costs savings

Introduction

Due to the continuing global competition for energy, together with stringent environmental legislations, batch industries are looking to renewable energies as a mean to reduce both footprint impact and operational costs. The main challenge of this solutions is the higher priority for industrial companies to have a reliable performance of the production process rather than the energy savings reached. Therefore, research to overcome this barrier and create solid and trustworthy models is required.

Heat integration

Papageorgiou, Shah, and Pantelides (1994) extended the discrete-time scheduling formulation of Kondili, Pantelides, and Sargent (1993) State-Task Network (STN) where opportunities for both direct and indirect heat integration were considered for the scheduling problem. More recently, Ana Paula F D Barbosa-Póvoa, Pinto, and Novais (2001) extended the work of A P Barbosa-Póvoa and Macchietto (1994) to consider heat-integration technologies at the plant design. However, economic savings were not considered. Later, Pinto, Barbosa-Povoa, and Novais (2003) extended the model to address this gap. T Majozi (2006) embedded heat integration in the continuous-time scheduling framework State-Sequence-Network SSN solving both scheduling and direct heat integration problems simultaneously.. Thokozani Majozi (2009) extended his previous work by including predefined heat storage for more energy savings. Later Stamp and Majozi (2011) addresses the optimization of heat storage size and initial temperature of heat storage medium. The resulting model exhibits MINLP.

Solar heat integration

Struckmann, Fabio (2008) formulated a mathematical model which describe the thermal performance of the collector in a computationally efficient manner. Salcedo et al. (2012) addresses the optimal design of desalination plants that integrate a parabolic trough solar collector. A multi-objective mixed-integer nonlinear programming model (MINLP) is developed to model such an integrated system and optimize its design. Omu et al. (2016) developed a mixed integer linear programming (MILP) model to facilitate the design of a solar domestic hot water system. Wallerand et al. (2016) created a MILP mode for optimal design and operation of a solar heated industrial process with constant heating requirements.

Problem Statement

The optimal plant design can be obtained by solving the following problem:

Given:

- The product recipes describing the production of one or more products over a single campaign
- The plant flowsheet with all possible equipment units to be installed
- The units suitability to perform the process/storage tasks.
- Task operating temperature,
- The utilities requirements and heat-integration options.
- The plant heat-transfer units.
- The operating and capital cost data involved in the plant/process installation and operation.
- The time horizon of planning.
- The production requirements over the time horizon.
- Allowed minimum temperature differences.
- Design capacity limits of heat storage unit and solar field.
- Solar irradiation profile,
- All data related with the solar collector

Determine:

- The optimal plant configuration
- A process schedule making use of the selected resources to achieve the required production
- Heat-transfer policies
- The optimal direct and indirect plant integration using external fluids.
- Utilities requirements.
- Number of solar collectors to install.
- Heat storage capacity.

So as to optimize the economic performance of the plant, measured in terms of the capital expenditure and the operating costs and revenues.

Mathematical Formulation

Sets

Task $i \in I$ = set of processing, material storage, charge and discharge tasks,

Unit $j \in J$ = set of processing, material storage and Thermal Energy Storage (TES) units,

State $s \in S$ = set of states,

$\mathrm{I_j}$ = {i: set of tasks which can be performed in unit j},

$\mathrm{J_i}$ = {j: set units suitable for task i},

$\mathrm{I^p}$ = {i: set of processing tasks},

$\mathrm{J^p}$ = {j: set of processing units},

$\mathrm{J^s}$ = {j: set of dedicated material storage units},

$\mathrm{J_s^s}$ = {j : set of dedicated storage units suitable for storing state s},

$\mathrm{K_j}$ = {k: set of k types of unit j},

$\mathrm{I_s^o}$ $/\mathrm{I_s^{in}}$ = {i: set of tasks producing/receiving material to state s},

$\mathrm{S^R}$ $/S^\mathrm{F}$ = {s: set of product/feed states}.

Utility $\mathrm{u} \in \mathrm{U}$ = set of utilities,

Heat-transfer unit $\mathrm{h} \in \mathrm{HE}$ = set of units suitable to transfer heat,

$HI_{i',i}$ = {h: set of units suitable to transfer heat between tasks $(i', i) \in I^{it}$ },
I_u = {u: set of tasks that can use utility u},
U_i = {u: set of utilities suitable for task i},
I^e = {i: set of processing exothermic tasks suitable for integration},
I^e = {i: set of processing endothermic tasks suitable for integration},
I_j^c = {i: set of tasks that charge TES unit j},
I_j^d h = {i: set of tasks that discharge TES unit j},
J^T = {j: set of TES units},
I^{it} = {$(i'/j', i/j)$: set of heat-integrated tasks},
Z^T = {z: set of z volumes of TES unit},
Z^s = {z: set of z numbers of solar panels},
M = Big M,
p_i = processing time of task i,
$\rho_{i,s}^{it}/\rho_{i,s}^{o}$ = proportion of material of state s entering/leaving task i,
$\emptyset_{i,j}^{m}$ /$\emptyset_{i,j}^{m}$ = maximum/minimum utilization factor of task i,
$V_{j,k}^{m}$ /$V_{j,k}^{m}$ = maximum/minimum capacity of unit j of type k,
$\emptyset_{s,j}$ = size factor of state s in storage unit j,
Q_s^m /Q_s^m = minimum/maximum production requirements,
$B_{u,t}^{m}$ = maximum availability of utility u at time t,
cp_u = heat capacity of utility u,
ΔT_u = temperature difference assumed for utility u,
ξ_i = predefined time offset of task i before integration,
$\mathrm{Q}_{i\theta}/\mathcal{B}_{i\theta}$ = fixed/variable heat demand factor of task i at processing time θ,
A_h^m /A_h^m = maximum/minimum heat-transfer area of unit h,
$p_{i',i}$ = integration time of tasks $(i', i) \in I^{it}$,
$\Delta Tln_{i'i}$ = mean fluid logarithmic temperature difference inside unit h when performing integration of tasks $(i', i) \in I^{it}$,
CU_h = overall heat transfer coefficient of unit h,
cp_w = Heat capacity of storage fluid,
T_i = process temperature of task i,
T^T /T^T = maximum/minimum TES temperature,
V_z^T = possible z volumes of TES unit,
R_z^T = thermal resistance for TES unit with volume z,
ρ_w = density of storage fluid,
Y^{lc} = TES unit overnight heat loss coefficient,
ΔT_m = minimum allowable thermal driving force for integration,
T^a = ambient temperature,
G_t = hourly solar radiation,
$\tau\alpha$ = solar collector optical efficiency,
UL = solar collector 1st order heat loss coefficient,
A^{S} = surface area of one solar collector,
B^S /B^S = maximum/minimum flowrate inside solar collector k,
N_z^{S} = given number z of solar collectors connected to TES unit,
ΔT^{S} = fluid temperature rise inside the solar collector,
HoursYr = number of annual working hours,
CCF = capital charge factor,

v_s/p_s = value/price of state s,

$OC^0_{i,j}/OC^1_{i,j}$ = fixed/variable operating cost of task i in unit j,

OC^0 $/OC^1$ = fixed/variable operational cost of solar task,

OC_s = operating cost of dedicated storage of state s,

OC^U_u = batch size dependent operational cost of utility u,

$CC^0_{j,k}/CC^1_{j,k}$ = fixed/variable capital cost of unit j of type k,

CC^0 $/CC^1$ = fixed/variable capital costs of TES unit,

CC^0_h $/CC^1_h$ = fixed/variable capital costs of heat transfer unit h,

CC^0 $/CC^1$ = fixed/variable capital costs of solar collector of type k,

Binary variables

$E_{j,k}$ = 1, if unit j of a given type k is installed; 0, otherwise,

E_j = 1, if unit j is installed; 0, otherwise,

E_h = 1, if heat-transfer unit h is installed; 0, otherwise,

$E^T_{j,z}$ = 1, if TES unit j with volume z is installed; 0, otherwise,

$E^{Sl}_{j,z}$ = 1, if z solar collectors are connected to TES unit j; 0, otherwise,

$W_{i',i,h,t}$ = 1 if unit h is performing heat-integration of tasks $(i', i) \in I^{it}$, at the time t; 0, otherwise,

Continuous variables

$B_{i,j,t}$ batch of task i in unit j at the start time t,

V_j capacity of processing unit j ,

$S_{s,t}$ amount of material in state s at the beginning of period t,

$D_{s,t}$ amount of material delivered from state s at the beginning of period t,

$R_{s,t}$ amount of material received from state s at the beginning of period t,

$B^U_{u,i,t}$ utilization level of external utility u by task i at the beginning of period t,

$Q^U_{i,t}$ heat supplied to task i by external utility u at the beginning of period t ,

A_h heat-transfer area of unit h,

$Q_{i',i,h,t}$ heat transferred between tasks $(i', i) \in I^{it}$, through heat transfer unit h at the beginning of period

$Q_{i,t}$ heat required by processing task i during time t,

$Q^{lo}_{j,t}$ amount of energy lost from TES unit j during time t,

$Q^S_{j,t}$ amount of energy stored in TES unit j at the beginning of time t,

$T^T_{j,t}$ mean temperature of TES unit j at the beginning of time t,

$T^T_{j,z,t}$ mean temperature of TES unit j with volume z at the beginning of time t,

$\eta_{j,t}$ efficiency of solar collector connected to TES unit j at time t,

$T^c_{j,t}$ average fluid temperature inside solar collector connected to TES unit j at time t,

$T^{in}_{j,t}$ solar collector inlet fluid temperature coming from TES unit j at time t,

$T^o_{j,t}$ solar collector outlet fluid temperature going to TES unit j at time t,

$B^{Sl}_{j,t}$ mass flowrate supplied to solar field at time t, connected to TES unit j,

$Q^{Sl}_{j,t}$ solar heat charged to TES unit j at time t,

STN model

Processing unit existence constraints.

A processing unit *j*, if chosen to be installed in the plant, can only exist in a single given type:

$$\sum_{k \in K_j} E_{j,k} = E_j$$

$\forall j \in J^p \cup J^{s}$

The processing unit *j* existence is linked to the allocation of the suitable tasks according to the following rules:
(1) at any time point each unit is either idle or processing a single task,

(2) tasks cannot be pre-empted once they have been started.

$$\sum_{i \in I_j \cap I^p} \sum_{\theta=0}^{p-1} W_{i,j,t-\theta} \leq 1$$

$\forall j \in J^p$

Capacity and batch size constraints. For each unit *j* the amount of material processed at any time point must be either zero or within the equipment capacity.

$$0 \leq B_{i,j,t} \leq M \cdot W_{i,j,t}$$

$\forall i \in I^p, j \in J_i, t = 1, \ldots, H$

$$\emptyset_{i,j}^{m} \cdot V_j - M \cdot (1 - W_{i,j,t}) \leq B_{i,j,t} \leq \emptyset_{i,j}^{m} \cdot V_j$$

$\forall i \in I^p, j \in J_i, t = 1, \ldots, H$

Using the existence variable $E_{j,k}$, the range of the available capacities for unit j can be defined by

$$\sum_{k \in K_j} V_{j,k}^{m} \cdot E_{j,k} \leq V_j \leq \sum_{k \in K_j} V_{j,k}^{m} \cdot E_{j,k}$$

$\forall j \in J^p \cup J^{s}$

Storage constraints.

$$0 \leq S_{s,t} \leq \emptyset_{s,j} \cdot V_j$$

$\forall s, j \in J_s^{s}, t = 1, \ldots, H+1$

Mass balances. For each state and at any time point *t* the amount of material present in that state is related to the amount produced, consumed and transferred by all incident tasks. Thus we have:

$$S_{s,t} = S_{s,t-1} + \sum_{i \in I_S^{i}} \sum_{j \in J_i} \rho_{i,s}^{i} \cdot B_{i,j,t} - \sum_{i \in I_S^{o}} \sum_{j \in J_i} \rho_{i,s}^{o} \cdot B_{i,j,t} - D_{s,t} + R_{s,t}$$

$\forall s, t = 1, \ldots, H+1$

Production requirement constraints. The production requirements are allowed to float within given upper and lower bounds.

$$Q_s^{m} \leq S_{s,H+1} - S_{s,0} + D_{s,H+1} \leq Q_s^{m}$$

$\forall s, S^F$

Global heat supply constraints. The hourly heat $Q_{i,t}$ required by or removed from each task is based on a fixed and variable heat demand factors, respectively q_{i} and $\mathcal{B}_{i}$.

$$Q_{i,t} = \sum_{\theta=0}^{p_i-1} \sum_{j \in J_i} \mathrm{q}_{i} W_{i,j,t-\theta} + \mathcal{B}_{i} B_{i,j,t-\theta}$$

$\forall i \in I^p, t = 1, \ldots, H$

The heating or cooling of each task is satisfied primarily by heat-integration $Q_{i',i,h,t}$, either in a direct or indirect form, and additionally if required, by external utilities $Q_{u,i,t}^{U}$.

$$Q_{i',t} = Q_{i',t}^{U} + \sum_{i} \sum_{h \in H_{i',i}} Q_{i',i,h,t}$$

$\forall i' \in I^e, t = 1, \ldots, H$

$$Q_{i,t} = Q_{i,t}^{U} + \sum_{i'} \sum_{h \in H_{i',i}} Q_{i',i,h,t}$$

$\forall i \in I^E, t = 1, \ldots, H$

External utilities constraint.

Given the utility heat capacity cp_u as well as its assumed temperature difference ΔT_u, necessary quantity $B_{u,i,t}^{U}$ to cool/heat task i is given by

$$Q_{i,t}^{U} = \sum_{u \in U_i} B_{u,i,t}^{U} \cdot cp_u \cdot \Delta T_u,$$

$\forall i \in I^p, t = 1, \ldots, H$

limits on the utilities availability are ensured by

$$0 \leq \sum_{i \in I^p \cap I_u} B_{u,i,t}^{U} \leq B_{u,t}^{m}$$

$\forall u, t = 1, \ldots, H$

Heat-integrated task activation constraints. If a task is undergoing a heat-integration is should be activated according to the following rules:

1) start within a pre-defined time offset ξ_i before undergoing a heat-integration,
2) if active, it may operate in either integrated or standalone mode,
3) can only be integrated with only one compatible task at any time point.

$$\sum_{h \in H_{i',i}} \sum_{i} W_{i',i,h,t} \leq \sum_{j' \in J_{i'}} W_{i',j',t-\xi_{i'}}$$

$\forall i' \epsilon I^e, t = 1, \ldots, H$

$$\sum_{h \in H_{i',i}} \sum_{i'} W_{i',i,h,t} \leq \sum_{j \in \cup J_i} W_{i,j,t-\xi_i}$$

$\forall i \epsilon I^e, t = 1, \ldots, H$

Heat-transfer unit allocation constraint. The allocation of heat transfer unit t is done according to the following rules:

(1) at any time each heat-transfer unit *h* is either idle or processing a single heat-integration task,

(2) heat-integration cannot be stopped once it has been started.

$$\sum_{\theta=0}^{p_{i'i}-1} \sum_{i'} \sum_{i} W_{i',i,h,t-\theta} \leq 1$$

$\forall h \in H_{i',i}, (i', i) \epsilon I^{l_i}, t = 1, \dots, H$

Heat-integration equipment design constraints. The required heat transfer units to be installed in the plant and their optimized heat-transfer areas are given by:

$$C_h \cdot A_h \cdot \Delta \mathrm{Tln}_{i',i} \geqslant Q_{i',i,h,t}$$

$\forall h \in H_{i',i}, t = 1, \dots, H$

$$E_h \cdot A_h^m \leq A_h \leq A_h^m \cdot E_h$$

$\forall h$

Since it is possible to accomplish the heat-transfer, then it is necessary to guarantee that the associated integration task occurs.

$$Q_{i',i,h,t} - M \cdot \sum_{\theta=0}^{p_{i'i}-1} W_{i',i,h,t-\theta} \leq 0$$

$\forall h \in H_{i',i}, t = 1, \dots, H$

TES unit allocation. Each TES unit *j* can only be integrated with one exothermic or endothermic task at any time point. Also the indirect heat-integration cannot be stopped once it has been started.

$$\sum_{\theta=0}^{p_{i'i}-1} \sum_{h \in H_{i',i}} \left[\sum_{i' \in I^e} \sum_{i \in I_j^{ch}} W_{i',i,h,t-\theta} + \sum_{i' \in I_j^d} \sum_{h\, i \in I^e} W_{i',i,h,t-\theta} \right] \leq E_j$$

$\forall j \in J^T, t = 1, \dots, H$

Energy balance constraints. At any time point the amount of energy stored in TES unit j is the sum of all the energy charged, discharged and lost.

$$Q_{j,t}^s = Q_{j,t-1}^s + \sum_{h \in H_{i',i}} \left[\sum_{i' \in I^e} \sum_{i \in I_j^{ch}} Q_{i',i,hi,t-1} - \sum_{i' \in I_j^d} \sum_{h\, i \in I^e} Q_{i',i,hi,t-1} \right] - Q_{j,t-1}^{l_i} + Q_{j,t-1}^{s_i}$$

$\forall j \in J^T, t = 1, \dots, H+1$

The initial heat stored is lower or equal to the previous day minus the overnight heat loss.

$$Q_{j,0}^s \leq Q_{j,H+1}^s \cdot (1 - Y^{l_i})$$

$\forall j \in J^T$

TES temperature constraint. TES temperature is mostly dependent on the heat stored and the volume of the tank.

$$Q_{j,t}^s = \sum_{z \in Z^T} V_z^T \cdot \rho_w \cdot cp_w \cdot (T_{j,z,t}^T - T^a \cdot E_{j,z}^T)$$

$\forall j \in J^T, t = 1, \dots, H+1$

$$T_{j,t}^T = \sum_{\forall z \in Z^T} T_{j,z,t}^T$$

$\forall j \in J^T, t = 1, \dots, H+1$

$$E_j = \sum_{z \in Z^T} E_{j,z}^T$$

$\forall j \in J^T$

Heat loss constraint. The hourly heat loss is dependent on both temperature and thermal resistance R_z^T of TES unit j.

$$Q_{j,t}^{l_i} = \sum_{z \in Z^T} \frac{(T_{j,z,t}^T - T^A \cdot E_{j,z}^T)}{R_z^T}$$

$\forall j \in J^T, t = 1, \dots, H$

TES temperature limits constraints. The temperature inside TES unit j at any time point must be either zero or within the equipment capacity.

$$E_{j,z}^T \cdot T^T \leq T_{j,z,t}^T \leq E_{j,z}^T \cdot T^T$$

$\forall z \in Z^T, j \in J^T, t = 1, \dots, H+1$

The minimum thermal driving forces must be obeyed during an indirect heat-integration.

$$\mathrm{T}_{i'} - T_{j,t+1}^T \geq \Delta T_m - M \cdot \left(1 - \sum_{\theta=0}^{p_{i'i}-1} \sum_{h \in H_{i',i}} W_{i',i,h,t-\theta}\right)$$

$\forall i \in I_j^{ch}, j \in J^T, t = 1, \dots, H+1$

$$T_{j,t+1}^T - \mathrm{T}_i \geq \Delta T_m - M \cdot \left(1 - \sum_{\theta=0}^{p_{i'i}-1} \sum_{h \in H_{i',i}} W_{i',i,h,t-\theta}\right)$$

$\forall i' \in I_j^d\ h, j \in J^T, t = 1, \dots, H+1:$

$$T_{j,t}^T - \mathrm{T}_i \geq \Delta T_m - M \cdot \left(1 - \sum_{\theta=0}^{p_{i'i}-1} \sum_{h \in H_{i',i}} W_{i',i,h,t-\theta}\right)$$

$\forall i' \in I_j^d\ h, j \in J^T, t = 1, \dots, H+1$

Solar technology existence constraint. If the solar technology is installed in TES unit j, then this unit must exist.

$$E_j^{S_i} \leq E_j$$

$\forall j \in J^T$

Collector efficiency constraint. The collector efficiency $\eta_{j,t}$ varies with the hourly solar radiation G_t, ambient air temperature T^a and average collector internal fluid temperature $T_{j,t}^{CC}$

$$\eta_{j,t} = \tau\alpha - \mathrm{UL} \cdot \frac{(T_{j,t}^{C} - T^a)}{G_t}$$

$\forall j \in J^T \quad, t = 1, \ldots, H$

Collector internal fluid temperature constraints. For a first order analysis, the collector internal fluid temperature is assumed to be the linear average of the inlet $T_{j,t}^{I_i}$ and outlet $T_{j,t}^{O}$ temperatures (Atkins 2010)

$$T_{j,t}^{C} = \frac{T_{j,t}^{I} + T_{j,t}^{O}}{2}$$

$\forall j \in J^T \quad, t = 1, \ldots, H$

Inlet fluid temperature $T_{j,t}^{I_i}$ during a certain time period, must be equal to the average TES temperature during that period.

$$T_{j,t}^{I} = \frac{T_{j,t}^{T} + T_{j,t+1}^{T}}{2}$$

$\forall j \in J^T \quad, t = 1, \ldots, H$

Solar heat constraints. The solar heat collected by one panel depends on its surface area and efficiency, as well as the hourly solar radiation.

$$Q_{j,t}^{S_i} \leq G_t \cdot N_Z^{S_i} \cdot A^{S_i} \cdot \eta_{j,t} + M \cdot (1 - E_{j,z}^{S_i})$$

$\forall j \in J^T \quad, z \quad Z^s, t = 1, \ldots, H$

The binary $E_{j,z}^{S_i}$, selects number of collectors connected to TES unit j.

$$E_j^{S_i} = \sum_{z \in Z^S} E_{j,z}^{S_i}$$

$\forall j \in J^T$

The amount of solar heat collected also depends on the mass flowrate $B_{j,t}^{S_i}$ for a given fluid temperature rise ΔT^{S_i} inside the collector.

$$Q_{j,t}^{S_i} = B_{j,t}^{S_i} \cdot cp_w \cdot \Delta T^{S_i}$$

$\forall j \in J^T \quad, t = 1, \ldots, H$

$$\Delta T^{S_i} = T_{j,t}^{O} - T_{j,t}^{I_i}$$

$\forall j \in J^T \quad, t = 1, \ldots, H$

Mass flowrate limits constraints. The mass flowrate at any time point must be either zero or within the collectors' capacity.

$$\sum_{z \in Z^S} B^S \cdot N_Z^{S_i} \cdot E_{j,z}^{S_i} \leq B_{j,t}^{S_i} \leq \sum_{z \in Z^S} B^S \cdot N_Z^{S_i} \cdot E_{j,z}^{S_i}$$

$\forall j \in J^T \quad, t = 1, \ldots, H$

Objective Function

$$\max P = (P - R - O - O - O - O - O) \cdot \frac{H}{H} - (C + C + C + C) \cdot C$$

$$P = \sum_{s \in S^F} \left[(S_{s,H+1} - S_{s,o}) \cdot v + \sum_t D_{s,t} \cdot v \right]$$

$$R = \sum_{s \in S^R} \left[(S_{s,o} - S_{s,H+1}) \cdot p + \sum_t R_{s,t} \cdot p \right]$$

$$O = \sum_t \sum_{i \in I^P} \sum_{j \in J_i} (OC_{i,j}^0 \cdot W_{i,j,t} + OC_{i,j}^1 \cdot B_{i,j,t}) + \sum_s \sum_t OC_s \cdot S_{s,t}$$

$$O = \sum_t \sum_{i \in I^P} \sum_{u \in U_i} O_u^U \cdot B_{u,i,t}^U$$

$$O = \sum_t \sum_{i'} \sum_i \sum_{h \in HI_{i',i}} O_{i',i,h}^{0H} \cdot W_{i',i,h,t} + O_{i',i,h}^{1H} \cdot Q_{i',i,h,t}$$

$$O = \sum_{j \in J^T} \sum_t B_{j,t}^{S_i} \cdot OC^{S_i}$$

$$C = \sum_{j \quad p \quad \cup J^S} \sum_{k \quad K_j} (E_{j,k} \cdot CC_{j,k}^0 + V_j \cdot CC_j^1)$$

$$C = \sum_{j \in J^T} \sum_{z \in Z^S} (CC^{0T} + CC^{1T} \cdot V_Z^T) \cdot E_{j,z}^T$$

$$C = \sum_h C_h^{0H} \cdot E_h + C_h^{1H} \cdot A_h$$

$$C = \sum_{z \in Z^S} \sum_{j \in J^T} E_{j,z}^{S_i} \cdot (CC^{0S_i} + N_Z^{S_i} \cdot CC^{1S_i})$$

Case study

A multipurpose batch plant must be designed at a maximum profit so as to produce three main products S7, S8 and S10 respectively with 300 to 350 ton, 200 to 250 ton and 200 to 250 ton. The STN product recipe may be found in Figure 1.

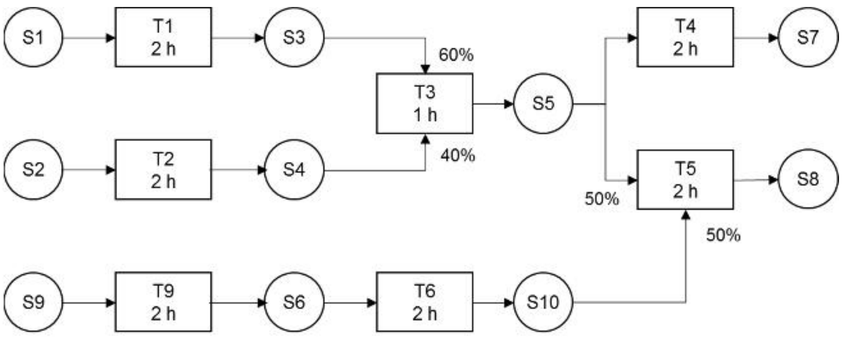

Figure 1. Product recipe STN

Economic characteristics are presented in Table 1, task characteristics may be found in Table 2, thermodynamic characteristics are presented in Table 3, equipment design and operational characteristics are shown in Table 5.. The optimal plant scheduling is presented in Figure 2.The optimal installed capacities are presented in Table 6 and the results summary is in Table 4.

The final objective function took the value of $24\,890 \cdot 10^3$ currency units. Total profit improved 19%, while external steam and water requirements dropped 61% and 77% respectively. The problem in study is characterized by 324 integer variables, 3333 constraints and was solved in 180 CPU seconds.

Parameter	Value	
Selling price of $s \in S^F$	100	c.u./ton
Purchase price of $s \in S^R$	5	c.u./ton
Steam cost	10	c.u./kWh
Cooling water cost	2	c.u./kWh
Task activation	20	c.u.
Heat transferred	1	c.u./kWh
Solar pumping costs	5	c.u./(ton)
Hours/Year	3000	h/year
Capital cost factor	33	%

Table 1. Economic characteristics

Parameter		Value
ΔT^m	ºC	10
$\Delta T_{i'i}$ (all i´,i)	ºC	10
C_h	kWh/m^2	3.6
T^T	ºC	100
T^A	ºC	25
cp_w	kWh/ton.ºC	1.19
A^{Sl}	m^2	1
τ	%	86.1
U	kWh	0.0048
ΔT^{Sl}	ºC	20

Table 3. Thermodynamic characteristics

Task	Type	Required kWh	T (ºC)
T1	Exothermic	7 + 0.5 B	80
T2	Endothermic	4 + 0.6 B	70
T3	Exothermic	9 + 1.3 B	120
T4	Endothermic	8 + 0.9 B	60
T5	Endothermic	6 + 0.8 B	70
T6	Exothermic	9 + 0.9 B	150
T9	Endothermic	2 + 0.2 B	80

Table 2. Task characteristics

	No heat integration	Heat + Solar integration	Δ
Profit (c.u 10³)	21 009	24 890	+ 19%
- Water (kwh)	1 565	609	- 61%
- Steam (kwh)	1 674	387	- 77%
- CPU time s	0.62	120	
- Binary Var.	95	324	
- Constraints	628	3 333	

Table 4. Results summary

Unit	Suitability	Capacity		Costs: Fix: Var
R1	T1	0:150	ton	5:0.05
R2	T2	0:150	ton	5:0.05
R3	T3/T6	0:400	ton	5:0.05
R4	T4	0:150	ton	5:0.05
R5	T5	0:150	ton	5:0.05
R6	T6/T9	0:200	ton	5:0.05
V1	S1	Unlim.	ton	3:0.01
V2	S2	Unlim.	ton	3:0.01
V3	S3	Unlim.	ton	3:0.01
V4	S4	Unlim.	ton	3:0.01
V7	S7	Unlim.	ton	3:0.01
V8	S8	Unlim.	ton	3:0.01
V9	S9	Unlim.	ton	3:0.01
V10	S10	Unlim.	ton	3:0.01
H1	R1-R2	0:15	m²	5:1
H3	R3-TES1	0:15	m²	5:1
H4	R4-TES1	0:15	m²	5:1
H5	R5-TES2	0:15	m²	5:1
H6	R6-TES2	0:15	m²	5:1
TES1	C1/D1	1:8	ton	5:1
TES1	C2/D2	1:9	ton	5:1
SOL1	TES1	10:400	un	5:2
SOL2	TES2	10:400	un	5:2

Table 5. Unit characteristics

Unit	Optimal Capacity	
R1	128	ton
R2	85	ton
R3	225	ton
R4	150	ton
R5	150	ton
R6	200	ton
H1	0.55	m²
H3	2.07	m²
H4	1.43	m²
H5	1.26	m²
H6	1.67	m²
TES1	5.8	ton
TES1	9	ton
SOL1	260	un
SOL2	390	un

Table 6. Optimal installed capacities

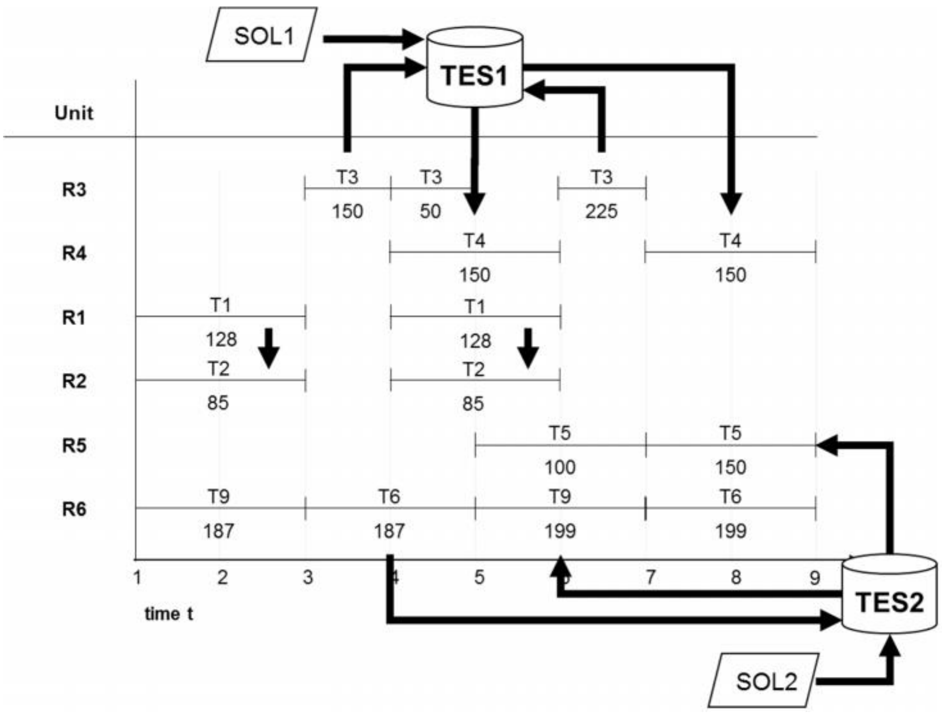

Figure 2. Optimal plant scheduling and heat transferred

Conclusions

A detailed mathematical framework for the design of multipurpose batch facilities with direct, indirect and solar heat integrations has been developed and tested. Optimal plant configuration and operation are obtained as well as optimal plant heat-transfer policies, heat-transfer units associated areas, heat storage volumes, and number of solar collectors. Important aspects were considered simultaneously, such as plant topology – the choice of the plant equipment – and plant operation, where the final scheduling is performed accounting for a set of heat-transfer policies. The problem was formulated through a mixed integer linear programming were binary variables define equipment choices and operability, and continuous variables define the equipment capacities and the amounts of material within the overall process. A new approach to bypass MINLP models was proposed, where size parameters were introduced to replace unwanted variables. Further work can be developed to assess the performance of this approach for more complex models.

References

Barbosa-Póvoa, A. P., & Macchietto, S. (1994). Detailed design of multipurpose batch plants. Computers & Chemical Engineering, 18(11–12), 1013–1042. Retrieved from https://doi.org/10.1016/0098-1354(94)E0015-F

Barbosa-Póvoa, A. P., Pinto, T., & Novais, A. Q. (2001). Optimal design of heat-integrated multipurpose batch facilities: a mixed-integer mathematical formulation, *25*, 547–559.

Kalogirou, S. A. (2004). Solar thermal collectors and applications. *Progress in Energy and Combustion Science*, *30*, 231–295. Retrieved from https://doi.org/10.1016/j.pecs.2004.02.001

Majozi, T. (2006). Heat integration of multipurpose batch plants using a continuous-time framework. *Applied Thermal Engineering*, *26*, 1369–1377. Retrieved from https://doi.org/10.1016/j.applthermaleng.2005.05.027

Majozi, T. (2009). Minimization of energy use in multipurpose batch plants using heat storage: an aspect of cleaner production. *Journal of Cleaner Production*, *17*(10), 945–950. Retrieved from https://doi.org/10.1016/j.jclepro.2009.02.013

Majozi, T., & Zhu, X. X. (2001). A Novel Continuous-Time MILP Formulation for Multipurpose Batch Plants. 1. Short-Term Scheduling. *Industrial & Engineering Chemistry Research*, *40*(25), 5935–5949. Retrieved from https://doi.org/10.1021/ie0005452

Omu, A., Hsieh, S., & Orehounig, K. (2016). Mixed integer linear programming for the design of solar thermal energy systems with short-term storage. *Applied Energy*, *180*, 313–326. Retrieved from https://doi.org/10.1016/j.apenergy.2016.07.055

Papageorgiou, L. G., Shah, N., & Constantinos, C. P. (1994). Optimal Scheduling of Heat-Integrated Multipurpose Plants. *Industrial & Engineering Chemistry Research*, *33*(12), 3168–3186. Retrieved from https://doi.org/10.1021/ie00036a036

Pinto, T., Novais, A. Q., & Barbosa-Póvoa, A. P. (2003). Optimal Design of Heat-Integrated Multipurpose Batch Facilities with Economic Savings in Utilities: A mixed integer mathematical formulation. *Annals of Operations Research*, *120*(1–4), 201–230.

Salcedo, R., Antipova, E., Boer, D., Jiménez, L., & Guillén-Gosálbez, G. (2012). Multi-objective optimization of solar Rankine cycles coupled with reverse osmosis desalination considering economic and life cycle environmental concerns. *Desalination*, *286*, 358–371. Retrieved from https://doi.org/10.1016/j.desal.2011.11.050

Stamp, J., & Majozi, T. (2011). Optimum heat storage design for heat integrated multipurpose batch plants. *Energy*, *36*(8), 5119–5131. Retrieved from https://doi.org/10.1016/j.energy.2011.06.009

Struckmann, F. (2008). *Analysis of a Flat-plate Solar Collector,* Project Report MVK160 Heat and Mass Transport. Lund, Sweden.