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Segregated Targeting for Resource Conservation with Dedicated Sources for Batch Process

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Conversation of natural resources is one of the most important steps towards sustainability and market competitiveness. Process Integration techniques have been successfully applied for conserving natural resources. High value-added products are the best suited in batch processes. The conservation of natural resources in batch processes is an important concern. A segregated targeting problem for the batch process is presented in this paper. This paper is focused on segregated targeting problems for optimal use of resources in the batch process through Pinch Analysis. The segregated targeting problem consists of internal sources, resources, dedicated sources and demands. Resource and dedicated sources of a given zone are used by demands of that zone only for a given period of time. Resources are time-independent and with no flow restrictions. Internal sources are also time-independent. Internal sources can be optimally used by any zones in a given time interval. An algorithm is developed so that internal sources can be used in such a way as to minimize resource requirements. This algorithm can be applicable for both semi-batch and batch processes. The applicability of the proposed algorithm is demonstrated through an illustrative example.

1. Introduction

Chemical process industries utilize a very large amount of freshwater, cooling water, energy, hydrogen, raw materials and many other resources. These resources must be utilized in such a manner that they meet the needs of present without compromising with the needs of future i.e., resources must be utilized in sustainable manner. Efforts have been done by governments, industries and researchers to improve process efficiencies. These efforts have been done in different ways like to improve process methods, to improve energy efficiency, to utilize energy in optimal manners etc. The efficient uses of valuable resources like natural gas, coal, utility gas, steam, freshwater etc. have a good impact on environment. Conversation of natural resources is the most important step towards sustainability and market competitiveness. Process integration plays an important role in resources conservation. Many researchers proposed various methodologies to minimize resource requirements for continuous processes. These methodologies can't be directly applied for batch processes. Batch processes are more complex due to presence of an additional time dimension.
Bandyopadhyay et al. (2010) used concepts of Pinch Analysis to develop a decomposition algorithm. This algorithm is used to determine resource optimal solution for segregated targeting problems. Lee et al. (2009) worked on resource allocation network (RAN) in carbon –constrained energy sector planning for a special type of problem which consists of a set of sources and multiple sets of demands called zones. This type of problem is identified as a segregated targeting problem. Chaturvedi (2017) worked on minimizing energy requirements in batch water network using Pinch Analysis. Stampfli et al. (2019) worked on batch process integration and maximized the total heat recovery within the process. Chaturvedi (2020) used Pinch Analysis approach to calculate the power rating of resources required for minimizing the overall cost of electricity in hybrid power system. Foo et al. (2021) used P-graph methodology for watch batch process. Jain and Bandyopadhyay (2017) developed a rigorous methodology for segregated targeting problems with dedicated sources. These works on segregated targeting problems were focusing towards continuous processes. It can be noted that segregated targeting problems involving batch processes are not focused. The development of resource minimization techniques in segregated targeting problems for batch processes is not yet presented. It is so because

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continuous processes produce much larger volume of wastewater and also minimize much more resource as compared to batch processes. This is the reason industrial practitioners and researchers are more focused in continuous processes. High value-added products are the best suited in batch processes. This paper is focused on developing an algorithm for segregated targeting problems with dedicated sources in the batch process. The segregated targeting problem consists of internal sources, resources, dedicated sources and demands. There are different zones. Each zone consists of dedicated sources, demands and resources. Resources and dedicated sources of a given zone are used by demands of that zone only for a given period of time. Resources are time-independent and with no flow restrictions. Internal sources are also time- independent. Internal sources can be used by any zones in a given time interval.

2. Problem Statement and Mathematical Formulation

The general problem for segregated targeting for resource conservation with dedicated sources in the batch process may be mathematically stated as follow:

A set of N_S internal sources (I.S) is given. Each source (i=1, 2,….,N_S) produces a flow of F_{si} with quality of q_{si} at a definite time interval. A set of multiple zones (k=1,2,….N_k) is also present. Each zone consists of dedicated sources (D.S), demands and one resource at a definite time interval. Each dedicated source (l=1, 2,…N_{DSlk}) of k^{th} zone produces flow F_{DSlk} with quality q_{DSlk} at a given time interval. Resources are time-independent and have no flow restrictions. Each resource of a given zone (say k^{th}) has a quality q_{rk}. Each demand (j=1,2,…N_{Dk}) of k^{th} zone accepts a flow F_{Dk} with a maximum allowable quality of q_{Djk} from dedicated sources ,and resource of its own zone. It can also be accepted from internal sources at a given time interval.

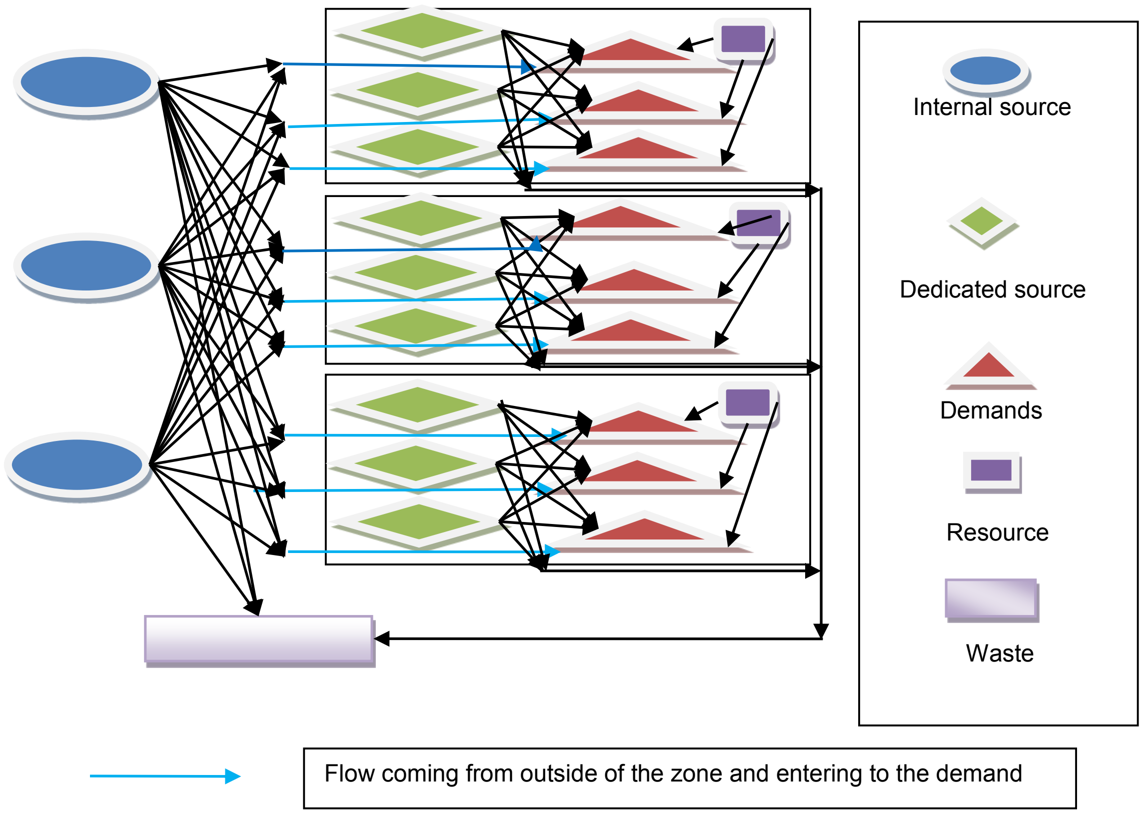

Figure 1: Superstructure of segregated targeting problem for a definite time interval

Flows and quantities are balanced based on superstructure as follow:

$$\sum_{k=1}^{Nk} \sum_{j=1}^{Ndk} f_{ijk}(t) + f_{iw}(t) = F_{si}(t) \qquad \forall i \tag{1}$$

$$\sum_{j=1}^{Ndk} X_{ljk}(t) + X_{lwk}(t) = F_{Dslk}(t) \qquad \forall l \tag{2}$$

$$\sum_{i=1}^{Ns}. f_{ijk}(t) + \sum_{l=1}^{NDSk}. X_{ljk}(t) + f_{rjk}(t) = F_{djk}(t) \qquad \forall j \tag{3}$$

$$F_{rjk}q_{rk}(t) + \sum_{i=1}^{Ns}. f_{ijk}q_{si}(t) + \sum_{l=1}^{NDSk}. X_{ljk}q_{DSlk}(t) \le F_{djk}q_{djk}(t) \tag{4}$$

$$W(t) = \sum_{i=1}^{Ns}. f_{iw}(t) = R(t) + \Delta(t) \tag{5}$$

$$\Delta(t) = \sum_{i=1}^{Ns}. F_{Si}(t) - \sum_{j=1}^{Nd}. F_{dj}(t) \tag{6}$$

$$\sum_{i=1}^{Ns}. f_{iw}(t) = \mathrm{W(t)} = R(t) + \sum_{i=1}^{Ns}. F_{Si}(t) - \sum_{j=1}^{Nd}. F_{dj}(t) \tag{7}$$

$$R(t) + \sum_{i=1}^{Ns}. F_{Si}(t) = W_{pinch}(t) + \sum_{j=1}^{Nd}. F_{dj}(t) \tag{8}$$

$$Rq_{rs}(t) + \sum_{i=1}^{Ns}. F_{Si}q_{si}(t) \le W_{pinch}q_p(t) + \sum_{j=1}^{Nd}. F_{dj}q_{dj}(t) \tag{9}$$

$$Rq_{rs}(t) + \sum_{i=1}^{Ns}. F_{Si}q_{si}(t) \le Rq_p(t) + \sum_{i=1}^{Ns}. F_{Si}q_p(t) - \sum_{j=1}^{Nd}. F_{dj}(t)q_p(t) + \sum_{j=1}^{Nd}. F_{dj}q_{dj}(t) \tag{10}$$

$$Rq_{rs}(t) - Rq_p(t) \le \sum_{i=1}^{Ns}. F_{Si}q_p(t) - \sum_{i=1}^{Ns}. F_{Si}q_{si}(t) - \sum_{j=1}^{Nd}. F_{dj}(t)q_p(t) + \sum_{j=1}^{Nd}. F_{dj}q_{dj}(t) \tag{11}$$

$$R(q_{rs} - q_p)(t) \le \sum_{i=1}^{Ns}. F_{Si}(q_p - q_{si})(t) - \sum_{j=1}^{Nd}. F_{dj}(q_p - q_{dj})(t) \tag{12}$$

$$R(t) \ge \sum_{j=1}^{Nd}. F_{dj}\frac{(q_{dj}-q_p)}{(q_{rs}-q_p)}(t) + \sum_{i=1}^{Ns}. F_{Si}\frac{(q_p-q_{si})}{(q_{rs}-q_p)}(t) \tag{13}$$

The objective is to minimize resource requirements

$$\text{Minimize } R = \sum_{j=1}^{Nd}. F_{dj}\frac{(q_{dj}-q_p)}{(q_{rs}-q_p)}(t) + \sum_{i=1}^{Ns}. F_{Si}\frac{(q_p-q_{si})}{(q_{rs}-q_p)}(t) \tag{14}$$

For minimizing R, the quantity $\frac{(q_p-q_{si})}{(q_{rs}-q_p)}(t)$ must be maximized. This quantity is known as Time Benefit Number (TBN).

$$TBN = \begin{cases} \frac{(q_p-q_{si})}{(q_{rs}-q_p)}(t), q_{rs} \ge q_p \\ \frac{(q_p-q_{si})}{(q_p-q_{rs})}(t),\ q_{rs} \le q_p \end{cases} \tag{15}$$

3. Proposed Algorithm

The following algorithm is proposed for solving segregated targeting problems with dedicated sources to minimize resource utilization in the batch process:

Step 1: Streams present in each zone are divided into definite time intervals. This step provides the availability of dedicated sources, demands, resources, and internal sources in a particular time interval

Step 2: Each zone is solved to determine resource requirements without use of internal sources in a particular time interval. This can be done by Pinch Analysis technique like Source Composite Curve, Limiting Composite Curve etc. This step provides resource requirements, pinch points etc. in a particular time interval.

Step 3: Calculate TBN Eq(15) in each zone for a particular time interval. The highest TBN is taken. The higher the value of TBN, the lower will be the resource requirement.

Step 4: Transfer a definite amount of flow from I.S to that zone which corresponds to the highest TBN. This step reduces resource requirements

Step 5: Transfer a definite amount of flow from I.S to that zone which corresponds to the next highest TBN. Continue this step until all TBNs of a particular time interval used or pinch point jumped. If this occurs then go to step 3

Step 6: Stop the algorithm if all internal sources are exhausted or all-time benefit numbers (TBNs) of all time intervals are used.

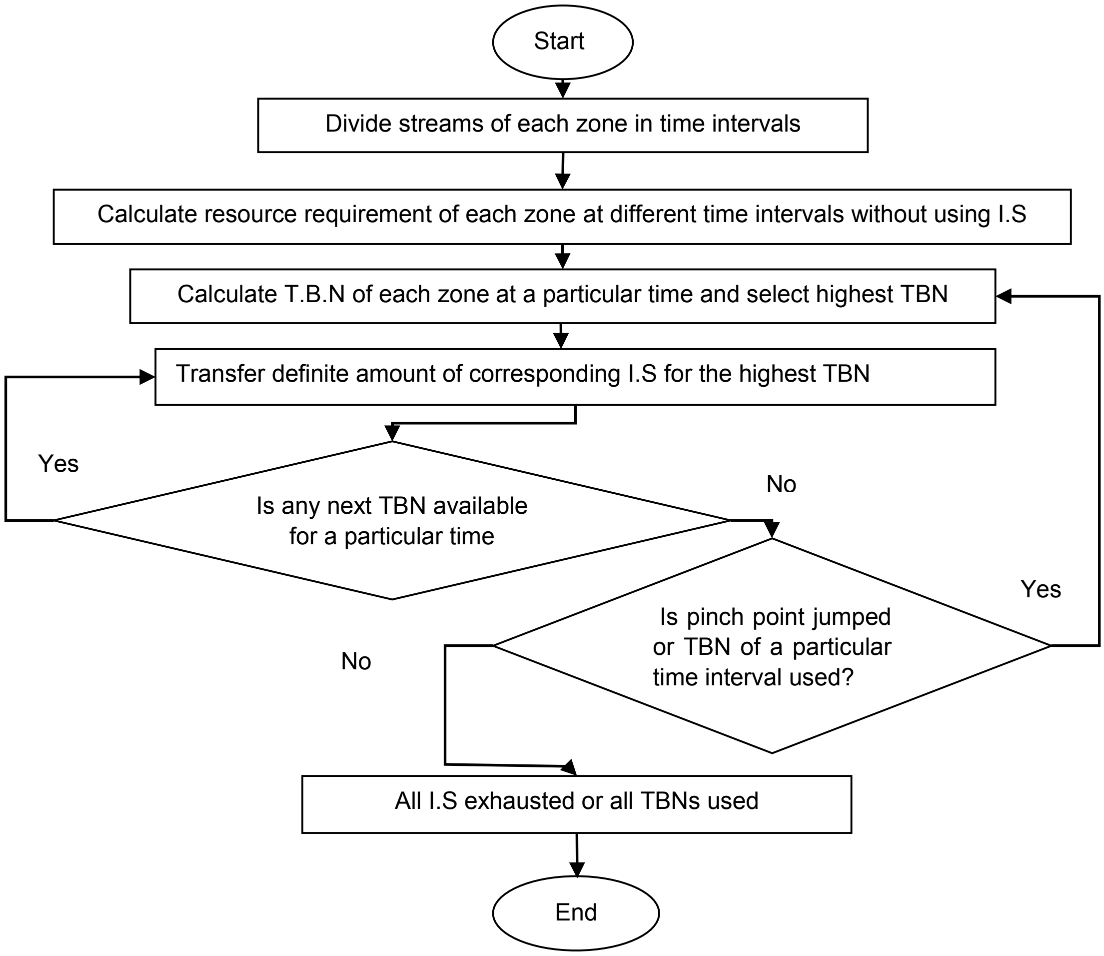

Figure 2: Flowchart for the methodology of segregated targeting problem in batch process

4. Illustrative example

The applicability of the proposed algorithm is demonstrated through an illustrative example. Consider a segregated targeting problem in which there are two zones and three internal sources. Each zone consists of three dedicated sources, three demands, and one resource. Dedicated sources and demands are time dependent while resources and internal sources are time –independent.

According to step 1, streams present in each zone are divided into equal time interval i.e., 0-1, 1-2, and 2-3 (h). This can be done by Gantt chart. Because of briefly, Gantt charts for both zones are not shown.

For zone 1, streams present in time interval 0-1,1-2, and 2-3(h) are R1, L2, D3; R1, L1, L2, L3, D1, D2, D3; and R1, L1, D1, D2, D3 respectively. For zone 2, the streams present in time interval 0-1, 1-2, and 2-3(h) are R2, L5, D4, D6; R2, L4, L5, L6, D5, D6; and R2, L4, D5, D6 respectively. After applying pinch analysis technique, freshwater requirements in zone 1 for time interval 0-1, 1-2 and 2-3(h) are 12.4667, 26.8 and 26.8t/h respectively. Pinch points in zone 1 for time interval 0-1, 1-2 and 2-3(h) are 20, 15 and 15 ppm respectively. Similarly freshwater requirements in zone 2 for time interval 0-1, 1-2 and 2-3(h) are 44.875, 39.22 and 39.22t/h respectively. Pinch points in zone 2 for time interval 0-1, 1-2 and 2-3(h) are 23, 17, and 17 ppm respectively. TBN for each zone at different time interval along with internal sources are calculated. For time interval 0- 1(h), TBNs for S1, S2 and S3 in zone 1 are 0, 0.33 and 0.467 respectively. Similarly, for time interval 0-1 (h), TBNs for S1, S2 and S3 in zone 2 are 0.231, 0.6154 and 0.769 respectively.

Table 1: Internal Source Data

Internal Source	Quality(ppm)	Flow(t/h)	Duration(h)
S1	20	22.45	0-3
S2	15	30.02	0-3
S3	13	58.96	0-3

Table 2: Zone 1 Data

Dedicated Source	Quality(ppm)	Flow(t/h)	Duration(h)
L1	15	40	1-3
L2	20	15	0-2
L3	22	7	1-2
Demands	Quality(ppm)	Flow(t/h)	Duration(h)
D1	10	15	1-3
D2	8	13	1-3
D3	9	17	0-3
Resource	Quality(ppm)	Flow(t/h)	Duration(h)
R1	5		0-3

Table 3: Zone 2 Data

Dedicated Source	Quality(ppm)	Flow(t/h)	Duration(h)
L4	17	50	1-3
L5	23	41	0-2
L6	25	50	1-2
Demands	Quality(ppm)	Flow(t/h)	Duration(h)
D4	7	23	0-1
D5	8	17	1-3
D6	9	25	0-3
Resource	Quality(ppm)	Flow(t/h)	Duration(h)
R2	10		0-3

For time interval 0-1 (h), the highest TBN is 0.769 which corresponds to zone 2 of S3; 8.33t/h is added from S3 to zone 2 which reduces freshwater requirement to 39.66t/h. The next highest TBN is 0.6154 which corresponds to zone 2 of S2, 0.0001t/h is added from S2 to zone 2, freshwater requirement does not change, it is still 39.66t/h (any amount of S2 does not change freshwater requirement). Again, the next highest TBN is 0.467 which corresponds to zone 1 of S3, 8.5t/h is added from S3 to zone 1, and freshwater requirement changes from 12.4667t/h to 8.5t/h. Further the subsequent highest TBN is 0.33 which corresponds to zone 1 of S2, 0.001 t/h is added from S2 to zone 1, freshwater requirement does not change, it is still 8.499= (8.5) t/h (any amount of S2 does not change freshwater requirement). The next highest TBN is 0.231 which corresponds to zone 2 of S1, 0.001 t/h is added from S1to zone 1, freshwater requirement does not change, it is still 39.66t/h (any amount of S1 does not change freshwater requirement).

For time interval 1-2 (h), TBN for S1, S2 and S3 in zone 1 are -0.5, 0 and 0.2 respectively. Similarly for time interval 1-2 (h), TBN for S1, S2 and S3 in zone 2 are -0.428, 0.2857 and 0.5714 respectively. The highest TBN is 0.5714 which corresponds to zone 2 of S3, 5t/h is added from S3 to zone 2 which changes freshwater requirement from 39.22t/h to37 t/h. The next highest TBN is 0.2857 which corresponds to zone 2 of S2, 0.0001 t/h is added from S2 to zone 2 which does not change freshwater requirement, it is still 37 t/h (any amount of S2 does not change freshwater requirement). The next highest TBN is 0.2 which corresponds to zone 1 of S3, 22.7498t/h is added from S3 to zone 1 which changes freshwater requirement from 26.8t/h to 22.25004t/h.

For time interval 2-3 (h), TBN for S1, S2 and S3 in zone 1 are -0.5, 0 and 0.2 respectively. Similarly for time interval 2-3 (h), TBN for S1, S2 and S3 in zone 2 are -0.428, 0.2857 and 0.5714 respectively. The highest TBN is 0.5714 which corresponds to zone 2 of S3, 5t/h is added from S3 to zone 2 which changes freshwater requirement from 39.22t/h to 37t/h. The next highest TBN is 0.2857 which corresponds to zone 2 of S2, 0.0001 t/h is added from S2 to zone 2 which does not change freshwater requirement, it is still 37t/h (any amount of S2 does not change freshwater requirement). Further the next highest TBN is 0.2 which corresponds to zone 1 of S3, 9.39t/h is added from S3 to zone 1 which changes freshwater requirement from 26.8 to 24.922t/h.

5. Conclusions

In this paper, a Pinch Analysis-based methodology is developed for segregated targeting for resource conservation with dedicated sources for batch Process. Previous methodologies for resource optimization of segregated targeting problems with dedicated sources cannot directly be applied for the batch process. The applicability of the proposed algorithm is shown with help of an example. This algorithm gives an idea for those types of problems also in which sources are available for many parts or many zones of batch process plants. With help of this algorithm, these sources can be optimally utilized. The TBN used in this algorithm indicates that which zone and which internal source are first applied simultaneously for resource minimization because higher the value of the TBN, lower will be resource requirement. This algorithm minimizes resource requirement approximately 4.55t/h in the given example. This algorithm can be applied for cooling water network, carbon constrained energy sector planning, water allocation network, etc. Internal sources are available for all time. This makes the problem semi-batch process also. If internal sources are also present in different time intervals, then the problem becomes more complex and rigorous. A graphical method can be developed for this problem in future.

Nomenclature

$F_{si}(t)$	Flow rate of i^{th} internal source at a particular time interval (t/h)
$F_{djk}(t)$	Flow rate of j^{th} demand present in k^{th} zone at a particular time interval (t/h)
$F_{Dslk}(t)$	Flow rate of l^{th} dedicated source present in k^{th}zone at a particular time interval (t/h)
$f_{ijk}(t)$	Flow rate transferred from i^{th} internal source to j^{th} demand present in k^{th}zone at a particular time interval (t/h)
$f_{rjk}(t)$	Flow rate transferred from r^{th} resource to j^{th} demand both present in k^{th} zone at a particular time interval (t/h)
$f_{iw}(t)$	Flow rate transferred from i^{th} internal source to waste at a particular time interval (t/h)
$X_{ljk}(t)$	Flow rate transferred from l^{th}dedicated source to j^{th} demand both present in k^{th} zone at a particular time interval (t/h)
$X_{lwk}(t)$	Flow rate transferred from l^{th}dedicated source present in k^{th} zone to waste at a particular time interval (t/h)
$q_{si}(t)$	Quality of i^{th} internal source at a particular time interval (ppm)
$q_{djk}(t)$	Quality of j^{th} demand present in k^{th} zone at a particular time interval (ppm)
$q_{DSlk}(t)$	Quality of l^{th} dedicated source present in k^{th} zone at a particular time interval (ppm)
$q_{rk}(t)$	Quality of r^{th} resource present in k^{th} zone at a particular time interval (ppm)
$q_{pk}(t)$	Quality of pinch point of k^{th} zone at a particular time interval (ppm)
$R(t)$	Resource at a particular time interval (t/h)
$W(t)$	Waste at a particular time interval (t/h)

References

Bandyopadhyay, S., Sahu, G. C., Foo, D. C. Y., Tan, R. R., 2010, Segregated targeting for multiple resource networks using decomposition algorithm. AIChE Journal, 56, 1235– 1248

Bandyopadhyay, S.,2015, Mathematical Foundation of Pinch Analysis. Chemical Engineering Transactions, 45:1753–1758.

Chaturvedi N.D., 2017, Minimizing the Energy Requirement in Batch Water Networks, Industrial & Engineering Chemistry Research., 56(1), 241-249

Chaturvedi N.D., 2020, Cost optimal sizing of hybrid power systems: a pinch analysis approach, Chemical Engineering Transactions, 81, 973-978.

Foo,.D.C.Y.,Chew,L.X., Chong,T.L., Teh,W.H., Lam,H.L., Affery,A.P., Pang,C.H.,2021, A note for the extended p-graph model for the synthesis of batch water network. Process Integration and Optimisation for Sustainability, 1-12

Jain, S., Bandyopadhyay, S., 2017, Resource allocation network for segregated targeting problems with dedicated sources. Industrial & Engineering Chemistry Research 56 (46):13831–13843

Stampfli J.A., Lucas E.J., Olsen D.G., Krummenacher P., Wellig B., 2019, Batch Process integration: management of capacity-limited thermal energy storage by optimization of heat recovery, Chemical Engineering Transactions, 76, 1027-1032.