SIMULTANEOUS DESIGN AND LAYOUT OF BATCH PROCESSING FACILITIES

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Abstract

A mathematical formulation for the simultaneous design and layout of batch process facilities is proposed. The model determines simultaneously the optimal plant topology (i.e. the choice of the plant equipment and the associated connections), the layout (i.e. the arrangement of processing equipment storage vessels and their interconnecting pipe-work over a two-dimensional space) and the optimal plant operation.

The problem is formulated as a mixed integer linear problem; binary variables are introduced to characterise operational and topological choices. The applicability of the proposed model is illustrated via a representative example.

Keywords

Design, Layout, Batch Facilities, Optimization, Mixed Integer Linear Programming (MILP).

Introduction

The design of batch processing facilities involves a large number of interacting decisions. An important part of the latter is layout considerations concerning the spatial allocation of equipment items and their interconnections. Traditionally, such layout issues have been considered a posteriori once the main plant design task has been completed. However, the interactions of layout with the rest of the design decisions are often quite strong, and this renders a simultaneous approach more desirable.

Papageorgaki and Reklaitis (1991) addressed the general batch plant design problem where the main equipment was selected allowing a flexible unit-to-task allocation. Plant operation over several campaigns was studied and the optimal allocations of products to campaigns as well as the campaign lengths were determined. Later on, Barbosa-Póvoa and Macchietto (1994) studied a single campaign problem where different products could be produced. Plant topology was considered and the design problem led to the choice of both the main equipment items and the associated network of connections.

The layout problem within batch process facilities has recently been studied by several authors, mainly being treated as a stand-alone problem to be solved once the

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main equipment items and their interconnections have been determined. Georgiadis et al. (1998) used a space discretization technique to consider the allocation of equipment items to floors and the detailed layout of each floor. Also, Papageorgiou and Rotstein (1998) proposed a mathematical programming model for determining the optimal process plant layout; their model employed a continuous representation of space and took account of many important features of the plant layout problem. Finally, a simultaneous approach to plant design, scheduling and layout was adopted by Realff et al. (1996) for the case of pipeless batch plants.

This paper presents a mathematical formulation for the simultaneous design and layout problem of batch process facilities. Based on the design model proposed by Barbosa-Póvoa and Macchietto (1994), detailed layout aspects are studied using a generalised approach of the work recently proposed by Papageorgiou and Rotstein (1998). The resulting model determines simultaneously the optimal plant topology (i.e. the choice of the plant equipment and the associated connections), the optimal layout (i.e. the arrangement of processing equipment storage vessels and their interconnecting pipe-work over a two-dimensional space) as well as the plant operation.

The complications arising from operational conditions, suitability and availability of equipment, the various layout constraints and the presence of equipment items of various sizes are taken into account.

The problem is formulated as a mixed integer linear problem where binary variables are introduced to characterise operational and topological choices.

The applicability of the proposed model is illustrated via a representative example.

**Problem Representation**

The problem representation uses the *maximal State-Task Network (mSTN)* as defined by Barbosa-Póvoa (1994).

The process recipes are defined through a *State-Task Representation (STNs, Kondili et al. 1988)* and the plant is characterised through a normal flowsheet - *equipment network* of vessels, processing units and possible connections.

Having the process recipes and the plant description the *mSTN* automatically combines the operations and equipment network by performing the mapping between the plant and process networks. This mapping is defined by:

- The suitability of each unit in the equipment network to carry out processing tasks, to store material states;
- The suitability of connections to transport material states;
- The resources - equipment, utilities, operators, etc. - required by each task.

The main advantage of this representation is that it unambiguously and explicitly represents all, and only, the location of material states and the allocations of processing, storage and transfer tasks which are potentially necessary and structurally feasible within the problem in study.

**Problem Definition**

The simultaneous design and layout of batch facilities can be stated as follows.

*Given:*

- The STN descriptions of product recipes with associated parameters and resource requirements - equipment, utilities, etc.
- A plant superstructure - network of units and connections - with associated capacities and suitability.
- Equipment units space requirements.
- Production demands, a time horizon, operation mode and availability profiles of all resources.
- Capital costs for units and connections.
- Space and equipment allocation limitations within a two dimensional continuous space.

*Determine:*

- The plant configuration - equipment network and sizes.
- The plant layout – allocation of each equipment item (i.e. coordinates and orientation).
- An operations schedule - sizes, allocation and timing of all batches, storage and transfers.

*So as to minimize the* capital cost of the plant.

**Problem Characteristics**

The developed model allows the description of general processing networks described by multi-product and multipurpose plants.

A discretization of time into a number of intervals of equal duration is fixed a priori, with process events occurring at interval boundaries. Task processing times, operations horizon, etc. are integer multiples of the selected interval.

Design and operation decisions are represented by continuous variables (batch sizes, equipment capacities, amounts of materials, etc.) and discrete choices by binary variables (equipment existence, task allocations to equipment and time, etc.). Equipment items (units, dedicated storage and connections) are selected optimally from the defined plant superstructure while operation is optimized so as to satisfy all constraints.

Product requirements are defined for each product as fixed or variable within ranges, in distributed (with arbitrary time profiles) or aggregate (over a cycle, horizon, etc.) form. Demands (and supplies) may be associated to specific equipment.

Equipment items in discrete size range(s), mixed storage policies, shared intermediate material, material merging, splitting and recycling, in-phase and out-of-phase operation in any combination are allowed.
A single campaign structure with fixed product slate is assumed within a non-periodic operation.

The plant is defined within a two dimensional continuous space. Equipment items to be allocated in the available space are described by rectangular shapes.

Rectilinear distances are assumed providing a more realistic estimate of the piping costs as opposed to direct connections.

Finally, multiple equipment connectivity inputs and outputs are considered as well as space limitations.

These characteristics were modeled considering the following sets of constraints:

*Unit Allocation Constraints* – determine the assignment of units to processing tasks assuming that at any time each unit is idle or processing a single task and that a task cannot be pre-empted once started.

*Unit Capacity and Batch Size Constraints* – define the equipment requirements as well as the necessary capacity.

*Connectivity Constraints* – accounts for the plant topology, transfer capacity and connections suitability.

*Dedicated Storage Constraints* – dedicated vessels are designed based on operational storage needs.

*Mass Balances Constraints* – relate the amount in the state with the amount of material being produced, consumed and transferred by all incident tasks.

*Production Requirement Constraints* – production levels of any product are allowed to float within given upper and lower bounds.

*Equipment orientation constraints* - reflect the effect of the equipment orientation within the space availability.

*Distance Restrictions* – define the location of the equipment accounting for distance restrictions.

*Non-overlapping Constraints* – avoid the overlapping of equipment within the same area.

*Equipment Input and Output Constraints* – define the connections input and output points for each equipment item.

*Space Availability Constraints* – model the space availability accounting for the possible existence of restrictions.

Finally, the objective function is defined in terms of the capital cost of the plant. This accounts for the units and connections costs – a function of the selected equipment capacity, material and suitability. For the connections, the final piping length – rectilinear distance within the plant – is also considered.

All equations are expressed in linear form as well as the objective function, resulting in a MILP problem. This is solved by a branch and bound method using a standard package (CPLEX).

**Example**

A simple example is used to illustrate the applicability of the method presented. This is based on one of the examples solved by Barbosa-Póvoa and Macchietto (1994). A margin of optimality of 5% is assumed.

A plant must be designed to produce two different products through the following process recipe:

1. **Step 1 (task T1):** heat raw material S1 for 2 hours to produce the unstable intermediate S3. Let them react for 2 hours to form product P1.
2. **Step 2 (task T2):** process raw material S2 for 2 hours to form the intermediate S4. Mix intermediate material S3 with material S4 in the ratio of 60:40 and let them react for 4 hours to form product P1.
3. **Step 3 (task T3):** mix intermediate material S3 with material S4 in the ratio of 60:40 and let them react for 2 hours to form product P2.

The plant must be able to fulfil the production requirements of 80 tonne for materials P1 and P2 over a time horizon of 8 hr. The minimisation of the plant capital cost is considered as the main objective. The example is solved considering two different cases:

1. The stand-alone design problem, as proposed by Barbosa-Póvoa and Macchietto (1994), without layout considerations. The solution provides the final plant topology and associated schedule for an objective function defined as the cost of the units.
2. The design and layout problems are solved simultaneously using the model proposed in this paper. The solution provides the final plant topology, plant layout and schedule for an objective function defined as the total cost of units and connections. In this case a limited area availability is considered - 21 x 6 m² (X x Y).

The plant superstructure used is shown in Figure 1 and the equipment characteristics are given in Table 1.

### Table 1 – Equipment Characteristics

<table>
<thead>
<tr>
<th>Unit</th>
<th>Suitability</th>
<th>Capacity [tonne]</th>
<th>Costs [10^6 c.u.]</th>
<th>Dimensions length/depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>T1/T2</td>
<td>70</td>
<td>14</td>
<td>8 / 8</td>
</tr>
<tr>
<td>1b</td>
<td>T1/T2</td>
<td>70</td>
<td>15</td>
<td>6 / 4</td>
</tr>
<tr>
<td>1c</td>
<td>T1</td>
<td>70</td>
<td>18</td>
<td>6 / 2</td>
</tr>
<tr>
<td>2a</td>
<td>T3/T4</td>
<td>120</td>
<td>40</td>
<td>5 / 5</td>
</tr>
<tr>
<td>V1</td>
<td>Store S1</td>
<td>Unlim.</td>
<td>1</td>
<td>6 / 3</td>
</tr>
<tr>
<td>V2</td>
<td>Store S2</td>
<td>Unlim.</td>
<td>1</td>
<td>6 / 3</td>
</tr>
<tr>
<td>V4</td>
<td>Store S4</td>
<td>50</td>
<td>3</td>
<td>5 / 1</td>
</tr>
<tr>
<td>V5</td>
<td>Store P1</td>
<td>Unlim.</td>
<td>1</td>
<td>4 / 3</td>
</tr>
<tr>
<td>V6</td>
<td>Store P2</td>
<td>Unlim.</td>
<td>1</td>
<td>4 / 3</td>
</tr>
</tbody>
</table>

Connections Costs : 150 c.u./m (currency units/m)
Simultaneous Design and layout of Batch Processing Facilities

For case 1, the final plant is characterised by the choice of units 1a, 1b and 2a and the vessels V1, V2, V5 and V6. This corresponds to a capital cost of 73000 c.u. In operational terms unit 1a is performing task T1, unit 1b task T2 and unit 2a is a multi-task unit performing tasks T3 and T4. No intermediate storage was chosen.

For case 2, where aspects of operation, design and layout are considered simultaneously, the results obtained are different. In this case the units chosen are respectively 1b, 1c and 2a apart from tanks V1, V2, V5 and V6. This corresponds to a capital cost of 77000 c.u. The operational schedule and layout are respectively illustrated in Figures 2 and 3.

The different plant topology is explained by the space availability restrictions. In this context unit 1a, which needs higher space requirements (8/8) when compared with unit 1c (6/2), can not be installed in the final plant due to the total space availability (21/6). Indeed, when trying to optimise the layout of the plant topology obtained from case 1, with the space restrictions defined in case 2, an infeasible problem is obtained. This shows how it may be important to consider design and layout aspects simultaneously when designing the plant.

In terms of computer statistics the final results are shown in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>Nodes</th>
<th>CPUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>negligible</td>
</tr>
<tr>
<td>2</td>
<td>389</td>
<td>30.8</td>
</tr>
</tbody>
</table>

Both cases are solved quite efficiently, although it is worth noting that case 1 does not cover layout. However, our yet limited experience with the model shows that improvements can be made if some of the already model intrinsic layout characteristics are further explored such as equipment orientation and pipe-work distance calculations. This is now under development.

Conclusions

The simultaneous design and layout of batch facilities has been studied. The optimal plant configuration and operation were obtained. Important aspects were considered such as plant operation, plant topology - the choice of the plant equipment and the associated connections – and plant detailed layout - arrangement of processing equipment storage vessels and their interconnecting pipe-work over a two-dimensional space.

The problem was formulated through a Mixed Integer Linear Programming where binary variables define equipment choices, operability and space arrangement.

The present model seems promising and, as stated above, it is now under development by the authors in order to explore the modeling efficiency of the already embedded features as well as to consider more general features such as: cost of land, shop-floor sections and multi-floor plant layout, among others.

One of the main limitations of the model identified so far is related to the solution efficiency of large systems. In order to overcome this difficulty other solutions approaches are being addressed. These take advantage of the problem characteristics and will be published elsewhere.

Acknowledgments

This work has been supported by the program PRAXIS XXI - grant PRAXIS/2/2.1/TPAR/453/95.

References

