Optimal Process Plant Layout using Mathematical Programming

by

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Abstract

Increased competition led contractors and chemical companies to look for potential savings at every stage of the design process including the process plant layout. Decisions concerning the plant layout may affect the design, operation, production organisation, safety and construction of the plant. This work aims at developing new quantitative computer-aided methods in order to assist engineers in generating optimal process plant layouts to account for multifloor, safety and pipeless operation. A lot of research work from chemical and industrial engineers was mainly focused on single-floor process plant layout following a variety of approaches without considering the multifloor case in detail. Multifloor constructions though can reduce significantly land and operational costs and comply with current requirements for more compact plants. In this thesis efficient solution approaches are presented in order to solve the multifloor problem by determining the number of floors and the spatial allocation of equipment items to floors. A number of cost and management/engineering drivers are considered within the same framework, thus resolving various trade-offs at an optimal manner. A wide range of plants, regarding the size and the duty, have been tackled.

A number of accidents in chemical plants increased the public awareness and anticipation for consideration of safety aspects during early stages of the design process. So far, they have been included in a rather simplified way in the process plant layout problem and the need for an in depth consideration is evident. Here, two different approaches are presented deciding on the allocation of items to the land area, the

number and type of the protection devices installed at the items and the financial risk associated with accidents.

The pipeless batch plant problem has only recently attracted the interest of the research community. Layout decisions about the allocation of processing stations in the land area are very important as they determine the vessel transfer times and affect the scheduling of both operation of processing stations and movement of vessels. In this work, a single-level approach is presented capturing layout, design and planning aspects of pipeless plants within the same framework.

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Chapter 1

Introduction

The process plant layout problem involves decisions concerning the spatial allocation of equipment items and the required connections among them (Mecklenburgh, 1985). In general, the process plant layout problem may be characterised by a number of cost and/or management/engineering drivers such as:

- *Connectivity Cost*: involving cost of piping and other required connections between equipment items. In addition, other related network operating costs such as pumping may be taken into account;
- *Construction Cost*: leading to the design of compact plants and particularly significant in cases such as off-shore platforms. The trade-off between the cost of occupied area (land) and height (multi-floor plants) must also be considered;
- *Retrofit*: fitting new equipment items within an existing plant layout;
- *Operation*: involving scheduling issues (e.g. pipeless plants);

- *Safety*: introducing, for example, constraints with respect to the minimum allowable distance between specific equipment items. Trade-offs between connectivity, pumping, construction, financial risk and installation of potential protection devices will be considered; and

- *Production Organisation*: facilitating the movements of goods and operators through the plant. Frequently, the accommodation of a specific manufacturing pattern (*e.g.* the organisation of the workforce into teams, working in well defined plant sections) may also be of great importance.

Usually, plant layout decisions are ignored or do not receive appropriate attention during the design or retrofit of chemical plants. However, increased competition led contractors and chemical companies to look for potential savings at every stage of the design process by focusing their research on the facility and process plant layout problem. Approaches for both problems were based on heuristics, graph partitioning, stochastic optimisation and mathematical programming techniques as described in detail in chapter 2.

During the layout of chemical plants, there is a growing concern about safety aspects that should be taken into account as they are usually not considered systematically within process layout, design and operation frameworks thus resulting in inefficient and unsafe plants. It is anticipated that safety aspects should be considered during early stages of the design process by using appropriate quantitative indices. This will ultimately enhance the application of detailed hazard and operability study of plant equipment items, that is usually a time consuming process and also requires skilled personnel.

Pipeless batch plants have also recently received some attention as alternative to traditional batch plants due to their inherent flexibility (material can potentially be transferred between any two processing items - stations). Layout considerations have been found to be of particular significance in pipeless plants since the location of the processing stations determines the transfer times for the moving vessels.

Some of the most common limitations of existing methodologies on the above issues are the following:

- *Problem Representation*: This should describe adequately the realistic characteristics of the layout problem. The discrete-domain models, which have been used quite extensively, are often inadequate as they may provide suboptimal solutions or require significant computational resources. In contrast, these deficiencies can be alleviated by continuous-domain models, which have only recently attracted some attention for academic interest. Most of these models capture only part of the important layout issues, use unrealistic assumptions (e.g. Euclidean distances) or are applied to single-floor plants;

- *Multifloor Plant Layout*: This is a more recent approach in order to capture the new requirements for more compact plants and enclosed structures, the use of gravity in material transfer and the reduction of the land area cost;

- *Safety Aspects*: These are either ignored or considered by simplistic terms (e.g. minimum distances) particularly during early stages of process plant design.

In addition, there is usually no account of financial risk and installation of potential protection devices; and

- *Design and Operation*: These should be considered simultaneously with plant layout decisions in the case of pipeless plants where there are strong interactions between the above issues.

In this thesis, we focus on the above limitations by developing a systematic framework for the optimal process plant layout.

1.1 Aims and Objectives

This thesis aims at developing new quantitative computer-aided methods, which will assist process engineers in generating alternative chemical process plant layouts with reduced cost and enhanced safety.

The process plant layout problem can be defined as locating a given number of equipment items in one or multiple floors so as to optimise a performance criterion, subject to a variety of constraints determining orientation, non-overlapping, plant area and distances between items. Usually, the performance criterion includes terms such as piping cost, pumping cost, land and construction costs, financial risk and cost of potential protection devices.

In order to achieve the aim of delivering rigorous mathematical models and efficient solution methods for the plant layout problem, we set the following key objectives:

1. The development of a unified mathematical modelling framework addressing

aspects such as:

- Multi-floor process plant layout;
- Safety; and
- Layout, design and operation.

2. The development of optimisation-based algorithmic methods for the solution of the resulting mixed integer optimisation problems.

In chapter 2, each of these points is considered in detail.

1.2 Thesis Outline

The rest of the thesis is structured as follows:

Chapter 2 presents a critical view of past work on single and multi-floor facility and process plant layout, safe process plant layout and simultaneous layout, design and operation of pipeless plants.

In chapter 3, a general mathematical programming formulation for the multi-floor process plant layout problem is presented. The model extends the single-floor work of Papageorgiou and Rotstein (1998), which is based on a continuous domain representation.

In chapter 4, a decomposition approach capable of tackling larger flowsheets, without compromising the solution quality, is considered. This approach comprises of smaller problems, a master and a subproblem, which are solved iteratively until convergence with a given tolerance.

Chapter 5 presents a novel solution approach for the multi-floor process plant layout problem based on an iterative solution scheme. The new approach comprises of a master and a subproblem as the decomposition approach, but a separate algorithm is followed for the solution of the subproblem.

In chapter 6, two different mathematical programming approaches - a mixed-integer nonlinear programming (MINLP) and a mixed integer linear programming (MILP) model - considering the process plant layout with safety aspects are presented.

Chapter 7 suggests a unified mathematical framework capturing layout, design, and planning aspects within the same framework for pipeless plants.

Finally, chapter 8 concludes the thesis summarising the work that has been done and outlining possible directions for future work in the area of the process plant layout problem.

Chapter 2

Literature Survey

Plant layout is concerned with spatial arrangement of equipment items and can influence the profitability of the plant (Mecklenburgh, 1985). Equipment items are allocated to one floor (single-floor case) or many floors (multi-floor case) considering a number of cost and management/engineering drivers (*e.g.* connectivity, operation, land area, safety, construction, retrofit, maintenance, production organisation) within the same framework. In order to resolve various trade-offs at an optimal manner, a number of computer-aided methods have been developed.

The main research works in facility and process plant layout problems are reviewed in sections 2.1 and 2.2 respectively. Works focused on the safety aspects of the process plant layout problem are presented in section 2.3. The works related to pipeless plants and their layout issues are presented in section 2.4. Finally, in section 2.5 the motivation and the scope of this work is clarified in the light of the earlier work in this area.

2.1 Facility Layout and Location Problem

A first extensive approach of the layout problem is given by industrial engineers studying the *facility layout and location problem* in Francis and White (1974), where a given number of departments are located in the plane minimising the material handling costs subject to location restrictions and department and floor area requirements. Comprehensive reviews on the facility layout and location problem are presented in Kusiak and Heragu (1987) and Meller and Gau (1996).

The most relevant approach for the solution of the single-floor facility layout problem is the *Quadratic Assignment Problem* (QAP) (Koopmans and Beckman, 1957). It is a special case of the facility layout problem as it assumes equal area departments and *a priori* fixed and known locations. The objective function depends on the flows (interactions) and the distances between facilities. Many approaches are presented for the solution of the QAP. Lawler (1963) suggests a transformation of the QAP into an equivalent integer linear program which is solved through a branch and bound technique. Fortenberry and Cox (1985) consider a heuristic approach where the total work flow is first weighted according to closeness rating between departments and then minimised. Kaku *et al.* (1991) also present a combination of a constructive heuristic method with exchange procedures. Combined methods to achieve quantitative and qualitative goals are also suggested (Bazaraa and Kirca, 1983; Adams and Sherali, 1986). According to Kusiak and Heragu (1987) reformulations of the QAP to include unequal area departments by breaking them into small equal area grids and assigning large interactions between grids of the same department are not proved successful to solve even small examples.

Another approach for the solution of the facility layout problem is based on graph theory (Foulds, 1991) which maximises an objective function of weights of the adjacencies (arcs) between department pairs (nodes).

Genetic algorithms also solve the problem providing reasonably good layouts (Al-Hakim, 2000). The flexibility of interactively modifying produced layouts or fixing departments is also considered (Kochhar *et al.*, 1998).

Finally, the single-floor facility layout problem is also solved in a continuous plane (avoiding the requirement of knowing *a priori* the potential locations) using either mixed integer programming (MIP) models minimising a distance-based objective (Montreuil, 1990) or MILP models, by applying a penalty method to an unconstrained version of the formulation obtaining suboptimal solutions quickly (Heragu and Kusiak, 1991).

A limited number of procedures are developed to solve the multi-floor facility layout problem. They can be divided in single stage and two-stage methods. In single stage procedures, departments are allowed to occupy any floor during execution. Johnson (1982) presents an algorithm which is likely to split them across different floors and is limited to exchange equal area or adjacent departments between floors. Bozer *et al.* (1994) overcome this limitation by utilising space-filling curves. Both works employ search with the steepest-decent method. Meller and Bozer (1996) on the other hand, suggest a simulated annealing based search outperforming previous methods.

In the two-stage procedures though, each department is assigned permanently to each floor in the first stage. In the second stage the layout is determined separately for each floor. Kaku *et al.* (1988) solve the first stage as a K-median problem (for equal area departments) and the second stage as a QAP. Meller and Bozer (1997) present two procedures combining mathematical programming (first stage) and simulated annealing (second stage). The second procedure permit also the reassignment of departments to different floors. Abdinnour-Helm and Hadley (2000) suggest two procedures where the first stage is solved either as an MILP or following a greedy randomised adaptive search procedure (GRASP) and the second stage with tabu search based heuristics. The second stage procedure in all cases may give suboptimal solutions compared to the single stage one, but the run times are considerably smaller.

2.2 Process Plant Layout Problem

Here, we focus on the *process plant layout problem* where a given number of equipment items are located in the plane minimising the total plant layout cost.

In the single floor case, initial approaches are based on heuristic techniques which they are efficient from the computational point of view but they do not guarantee optimality of the solution obtained. In Amorese *et al.* (1977), connection cost is minimised by imposing constraints for the non-interference of the areas of influence for each unit. The proposed model is solved by proposing a large number of heuristics achieving a 2% improvement from the initial layout. Suzuki *et al.* (1991a) include in the objective function preferences on equipment arrangements along with piping cost. Equipments items are grouped into modules and the modules into sections resulting in an MINLP model which is solved by a heuristic approach. Schmidt-Traub *et al.* (1998) develop a new method for the conceptual plant layout problem based on heuristic rules, statistical data and new algorithms for the new spatial arrangement of equipment items as well as pipe routing.

Graph theory approaches are also applied to the problem of organising items into sections created by aisles or corridors by representing the equipment and their connectivities with an edge weighted graph (Jayakumar and Reklaitis, 1994). Vertices are partitioned into subsets and the total weight of the edges joining vertices from different subsets is minimised.

Furthermore, stochastic optimisation techniques utilising genetic algorithms are proved to be effective in obtaining good and practical solutions for the enhanced process plant layout problem with safety aspects (Castel *et al.*, 1998).

A number of mathematical programming approaches are also suggested including MINLP and MILP approaches. In Penteado and Ciric (1996), plant layout aspects are integrated with safety and economics. A disadvantage of this work is the adoption of circular footprints and straight-line connections (Euclidean distances) between equipment items. Both assumptions are unrealistic as current industrial practices suggest rectangular shapes, in order to allow space for auxiliary instrumentation, piping and maintenance, and rectilinear (Manhattan) distances as the pipes are likely to follow piperacks (Penteado and Ciric, 1996; Papageorgiou and

Rotstein, 1998).

Continuous domain MILP models to determine optimal location (*i.e.* coordinates) and orientation for each equipment item are presented in Papageorgiou and Rotstein (1998). Two alternative formulations are proposed accommodating rectangular equipment footprints. One of the formulations is then extended to account for the layout organisation into production sections.

An alternative continuous formulation for equipment allocation, utilising a piecewise-linear function representation for absolute value functionals is presented in Özyruth and Realff (1999) where equipment orientation is not allowed. The new formulation is compared with the one from Papageorgiou and Rotstein (1998) and a hybrid formulation is then suggested.

Finally, Barbosa-Povoa *et al.* (2001) propose an MILP model considering different equipment orientation, distance restrictions, different connectivity inputs and outputs, irregular equipment shapes and space availability. The model is then extended to address the existence of production sections.

The multifloor process plant layout problem is a more recent approach in order to capture:

- Cases where the land area cost represents a considerable percentage of the total cost due to the geographical location of the plant site and a possible multifloor consideration may potentially reduce the total plant layout cost;

- New safety and environmental legislation requirements for more compact plants and enclosed structures. By this way, emissions can be monitored and contained more easily; and

- Use of gravity in material transfer to reduce operating costs considerably.

Current research works on this area include the assignment of items of multipurpose batch plants to different floors, by taking into account vertical pumping and land costs and satisfying a number of preferences (Suzuki *et al.*, 1991b). Approximations of the transportation and floor construction costs are used as the exact distances are not calculated. In Suzuki *et al.* (1991c), an integer programming model is proposed to arrange equipment items of a batch plant in a multi-floor building. Various types of preferences are considered and each unit is divided or combined with others into "components" and each component is assigned to one of the "positions" on a grid. A combination of a graphical heuristic approach and a mathematical programming formulation in order to allocate the units in different floors with no consideration of the detailed layout within each floor is proposed in Jayakumar and Reklaitis (1996). The heuristic approach provides an upper bound and the linearised integer nonlinear programming (INLP) formulation provides a lower bound to the optimal solution. A grid based MILP model is described in Georgiadis *et al.* (1997), based on space discretisation into a set of candidate locations, with each equipment item occupying only one location. The objective function to be minimised was the total pumping, connection and floor construction cost. Georgiadis *et al.* (1999) adopt a finer discretisation to account for equipment items with different sizes allowing them to occupy, potentially more than one floors. The MILP model determines the coordinates of each unit, the total piping length and the land occupied.

Finally, similar to the single floor approach, Barbosa-Povoa *et al.* (2002) present a number of topological characteristics in three MILP models. The first model describes a basic 3D layout model while the second and the third one are extensions of the former including multi-floor allocation of items accounting for fixed and variable number of floors and height. Flowsheets up to 11 equipment items are considered.

2.3 Process Plant Layout with Safety Aspects

Appropriate decisions on the process plant layout during the design or retrofit of a chemical plant may increase the safety of the plant. So far though, safety aspects are considered in a rather simplified way by allocating equipment items with respect to the minimum allowable distances between them. A number of accidents in chemical process industries in the last two decades (Khan and Abbasi, 1999) increased the public awareness of hazards in industry, thus leading to a need for considering safety aspects in more detail within process plant layout and design frameworks.

Particular attention to safety aspects of the process plant layout problem is given through a heuristic approach by Fuchino *et al.* (1997), where the equipment modules are divided into subgroups and then sub-arranged within groups according to safety. Then, these sub-arrangements are merged.

Genetic algorithm methods utilising the Mond Index (1995) also solve the problem efficiently (Castel *et al.*, 1998). The Mond Index provides the minimum safety distances between the process units and is chosen because of its simplicity and availability at early design stages.

Penteado and Ciric (1996), as mentioned earlier, propose an MINLP model determining simultaneously the process plant layout, the number and type of protection devices and the financial risk associated with accidents and their propagation to neighbouring items, assuming circular footprints of items. This work is based in a representation of the risk related to accidents propagating from a source to a target item utilising the equivalent TNT method (Lees, 1980).

2.4 Pipeless Plants

New environmental regulations, product specifications and demands and narrow profit margins in the last 15 years have forced chemical industries to look for more effective ways of production operations to remain competitive. Attention is now focused on the adaptability and flexibility of production operations of new plants or revamped existing plants. For example, the flexibility of batch plants on producing a large number of products is limited because of the need of equipment and piping cleaning especially in food and pharmaceutical production.

One promising option is the pipeless batch plants (Niwa, 1993). Their main difference from traditional batch plants is the transportation of material through *transferable vessels* from one processing stage to the other. The vessels may have individual built-in carts or may be carried by a shared pool of Automated Guide Vehicles (AGVs) and their motion can be free or take place on tracks. In the later case the system size, the charge/discharge time and the machine failure rate factor can significantly affect the operation of the system (Farling, 2001).

The processing takes place in *processing stations* of specific functions. According to Niwa (1991) the following 6 processing station types are most oftenly included in the batch recipes: (a) mixing; (b) reaction; (c) distillation; (d) extraction/isolation; (e) sampling/discharge; and (f) washing station. The same transfer vessels hold the material while processing at each station. The elimination of pipework offers great flexibility as any material can be transferred in the vessels between two different processing stations, offering quick respond to market demands. Cleaning performs normally in cleaning stations reducing possible extra time of cleaning of the stations and piping.

The pipeless plant problem have only recently attracted the interest of the research community. A heuristic methodology for the design of single-stage pipeless plants is presented by Hasebe and Hashimoto (1991). A solution to the aggregate problem of determining the number of transferable vessels and processing stations and an evaluation of the pipeless plants considering operational issues is suggested in Niwa (1993) and Niwa (1994) respectively. Pantelides *et al.* (1995) present a systematic and rigorous approach to the optimal detailed short term scheduling of pipeless plants. The MILP model exploits the flexibility of the plant equipments and accommodates recipes of arbitrary complexity. Liu and Mc Greavy (1996) present a framework which aims to consider and examine the design and the operating strategies of pipeless plants emphasising to dynamic analysis and production arrangements. Bok and Park (1998) present a short-term scheduling, MILP model for multipurpose pipeless plants over a continuous-time domain representation which emphasises representation of the various directions of production.

Plant layout involves decisions about the allocation of processing stations in the land area thus determining the vessel transfer times and affecting the scheduling of both operation of processing stations and movement of vessels. Realff *et al.* (1996) present a simultaneous approach considering design, layout and operation. A rigorous decomposition procedure is proposed for the solution of the resulting MILP. The layout structure is pre-selected and the model decides the position where each station should be allocated (discrete approach). Gonzalez and Realff (1998a) couple a discrete event simulator to schedules derived from MILP models and produce and compare two different layouts with the same equipment. Then the sensitivity of the MILP schedules to random perturbations in processing and travel times is evaluated. Gonzalez and Realff (1998b) compare the above MILP schedules to results obtained by using local dispatch rules to govern station operation and vessel movement.

2.5 Discussion

In sections 2.1 and 2.2, the main research works in the facility and process plant layout problems were presented. Most applications of the facility layout problem consider job shops and assembly facilities. Some of the weaknesses of the methods associated with the facility layout problem are the the usual assumptions of constant allocation of departments to locations and equal area departments and also the likelihood of splitting departments across two or more floors. Therefore, there is a need for a separate study of the process plant layout problem due to the additional levels of complexity of chemical processing.

There are three basic disadvantages in the approaches presented in section 2.2 for the process plant layout problem. The first is the provision of suboptimal solutions as many of them are based on heuristic rules or consider discrete domain models. The second is the non-compliance with current industrial practices by utilising Euclidean distances and circular footprints as clearly explained in the works of Penteado and Ciric (1996), Georgiadis *et al.* (1997) and Papageorgiou and Rotstein (1998). Finally, many of them are unable to tackle large flowsheets in reasonable computational times because of the increased model size.

For these reasons, there is a need for new mathematical formulations and new solution approaches particularly in the more promising and less investigated multifloor case to tackle large flowsheets in modest computational times utilising a continuous-domain representation. In chapters 3, 4 and 5 a simultaneous, a decomposition and an iterative approach are presented for the solution of the multi-floor process plant layout.

Considering safe process plant layouts, there is a need for an approach that combines process plant layout and detailed risk assessment. In chapter 6, quantitative safety evaluation systems like the Dow Fire and Explosion Hazard System (1994), which quantifies the expected damage caused by fire or explosion, can be considered in a process plant layout problem.

Research work should focus on the development of mixed integer optimisation models by incorporating safety aspects within single floor layout problems following realistic assumptions. The performance criterion used in these models should include terms such as financial risk and cost of protection devices. The financial risk component should reflect the consequences of building unsafe chemical plants and can therefore be quantified as the expected plant losses in case of accidents due to fire or explosion. In chapter 6, a mathematical formulation considering the above issues by utilising the equivalent TNT method (Lees, 1980; AIChE/CCPS, 1989) for the representation of the propagation of an accident from a source to a target unit.

Finally in the case of pipeless plants, there is no approach deciding simultaneously on the type of the layout and the allocation of processing stations in the land area of the pipeless plant. There is a need for a unified mathematical framework capturing layout, design, and planing aspects within the same framework. The resulting model should consider all the above components simultaneously thus resolving various trade-offs at an optimal manner. In Chapter 7 a new mathematical framework is presented extending the single-floor work of Papageorgiou and Rotstein (1998), which is based on a continuous domain representation, and the aggregate model describing the plant operation presented by Realff *et al.* (1996).

Chapter 3

Multifloor Process Plant Layout - A Simultaneous Approach

In this chapter, a simultaneous approach for the multifloor process plant layout problem is presented. The proposed general mathematical programming formulation extends the single-floor work of Papageorgiou and Rotstein (1998), which is based on a continuous domain representation. This type of representation compares favourably to the convenient, from the modelling point of view, grid-based approaches (Georgiadis *et al.*, 1997; 1999)) where equipment items are allocated to one or more candidate locations because they can guarantee global optimality. The MILP formulation determines simultaneously the number of floors, land area, floor allocation of each equipment item and detailed layout for each floor.

3.1 The Multifloor Process Plant Layout Problem

In the simultaneous approach presented here, rectangular shapes are assumed for equipment items following current industrial practices. Rectilinear distances between the equipment items are used for a more realistic estimate of piping costs (Penteado and Ciric, 1996; Papageorgiou and Rotstein, 1998; Georgiadis et al., 1999). Equipment items, which are allowed to rotate 90°, are assumed to be connected through their geometrical centres.

Overall, the multi-floor plant layout problem can be stated as follows:

Given:

- A set of N equipment items and their dimensions;
- A set of K potential floors;
- Connectivity network;
- Cost data (connection, pumping, land and construction);
- Floor height;
- Space and equipment allocation limitations; and
- Minimum safety distances between equipment items.

Determine:

The number of floors, land area, equipment-floor allocation and detailed layout (*i.e.* orientation, coordinates) of each floor.

So as to minimise the total plant layout cost.

Next, the mathematical formulation is presented.

3.2 Mathematical Formulation

The indices and parameters associated with the layout problem are listed below:

Indices

i, j equipment item

k floor

s candidate rectangular area

Parameters

f_{ij} 1 if flow is from item i to item j; 0 otherwise

AR_s area of rectangular area s $[m^2]$

C^c_{ij} connection cost between items i and j $[rmu/m^1]$

C^v_{ij} vertical pumping cost between items i and j $[rmu/m]$

C^h_{ij} horizontal pumping cost between items i and j $[rmu/m]$

$FC1$ fixed floor construction cost $[rmu]$

$FC2$ area dependent floor construction cost $[rmu/m^2]$

---

[1] *rmu* stands for relative money units

H floor height $[m]$

LC land cost $[rmu/m^2]$

M distance upper bound

$\overline{X}_s, \overline{Y}_s$ dimensions of rectangular area s $[m]$

α_i, β_i dimensions of item i $[m]$

The formulation is based on the following key variables:

Integer Variables

NF number of floors

Binary Variables

$E1_{ij}, E2_{ij}$ non-overlapping binary variables (as used in Papageorgiou and Rotstein; 1998)

O_i 1 if length of item i is equal to α_i (*i.e.* parallel to x axis); 0 otherwise

Q_s 1 if candidate area s is selected; 0 otherwise

V_{ik} 1 if item i is assigned to floor k; 0 otherwise

Z_{ij} 1 if equipment items i and j are allocated to the same floor; 0 otherwise

Continuous Variables

l_i length of item i $[m]$

d_i depth of item i $[m]$

x_i, y_i coordinates of geometrical centre of item i $[m]$

A_{ij} relative distance in y coordinates between items i and j, if i is above j $[m]$

B_{ij} relative distance in y coordinates between items i and j, if i is below j $[m]$

D_{ij} relative distance in z coordinates between items i and j, if i is lower than j $[m]$

FA floor area $[m^2]$

L_{ij} relative distance in x coordinates between items i and j, if i is to the left of j

$\overline{NQ}_s$ linearisation variable expressing the product of NF and Q_s

R_{ij} relative distance in x coordinates between items i and j, if i is to the right of j $[m]$

TD_{ij} total rectilinear distance between items i and j $[m]$

U_{ij} relative distance in z coordinates between items i and j, if i is higher than j $[m]$

X^{max}, Y^{max} dimensions of floor area $[m]$

3.2.1 Floor Constraints

Each equipment item should be assigned to one floor:

$$\sum_k V_{ik} = 1 \qquad \forall\, i \tag{3.1}$$

The value of the Z_{ij} variables can be obtained by:

$$Z_{ij} \geq V_{ik} + V_{jk} - 1 \qquad \forall\, i = 1..N-1, j = i+1..N, k = 1..K \tag{3.2}$$

$$Z_{ij} \leq 1 - V_{ik} + V_{jk} \qquad \forall\, i = 1..N-1, j = i+1..N, k = 1..K \tag{3.3}$$

$$Z_{ij} \leq 1 + V_{ik} - V_{jk} \qquad \forall\, i = 1..N-1, j = i+1..N, k = 1..K \tag{3.4}$$

Note that if two equipment items i and j are allocated to the same floor (*i.e.* $V_{ik} = V_{jk}$) then the corresponding Z_{ij} variable is forced to one by constraints (3.2), while constraints (3.3) and (3.4) are inactive. On the other hand, if equipment items i and j are allocated to different floors then constraints (3.2) are inactive while constraints (3.3) and (3.4) are active and force the Z_{ij} variable to zero.

The number of floors, NF, is determined by:

$$NF \geq \sum_k k \cdot V_{ik} \qquad \forall\, i \tag{3.5}$$

It should be added that constraints (3.5) will be active for the equipment items assigned to the top occupied floor given that the NF variable is minimised in the objective function (see section 3.2.6).

3.2.2 Equipment Orientation Constraints

The length and the depth of equipment item i are determined by equipment orientation decisions. The effect of equipment orientation is captured as follows:

$$l_i = \alpha_i \cdot O_i + \beta_i \cdot (1 - O_i) \qquad \forall\, i \tag{3.6}$$

$$d_i = \alpha_i + \beta_i - l_i \qquad \forall\, i \tag{3.7}$$

3.2.3 Non-overlapping Constraints

In order to avoid situations where two equipment items i and j occupy the same physical location when allocated to the same floor (*i.e.* $Z_{ij} = 1$), appropriate constraints should be included in the model that prohibit overlapping of their equipment footprint projections, either in x or y direction. If i and j are allocated to the same floor, then this constraint is depicted in Figures 3.1 and 3.2. Non-overlapping is guaranteed if *at least* one of the following inequalities is active:

$$x_i - x_j \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{3.8}$$

$$x_j - x_i \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{3.9}$$

$$y_i - y_j \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{3.10}$$

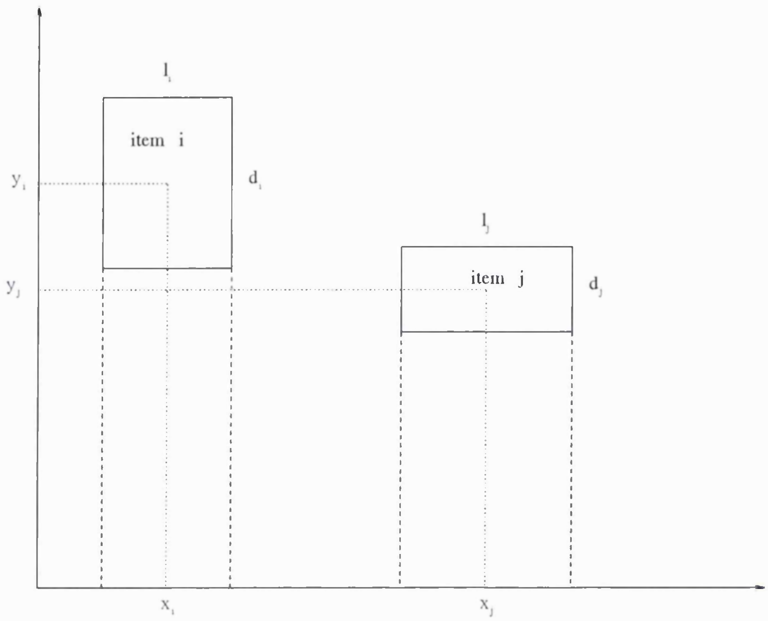

Figure 3.1: Avoiding equipment overlapping (x- direction)

$$y_j - y_i \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{3.11}$$

For instance, in Figure 3.1 inequality (3.9) is active while in Figure 3.2 inequality (3.10) is active. These non-overlapping disjunctive conditions can mathematically be modelled by including appropriate "big M" constraints and introducing two additional sets of binary variables; $E1_{ij}$ and $E2_{ij}$. Each pair of values (0 or 1) to these variables determines which constraint from (3.8) to (3.11) is active.

For every pair (i, j) such that $j > i$ and $Z_{ij} = 1$, we have:

If constraint (3.8) is active then :

$$E1_{ij} = 0, E2_{ij} = 0$$

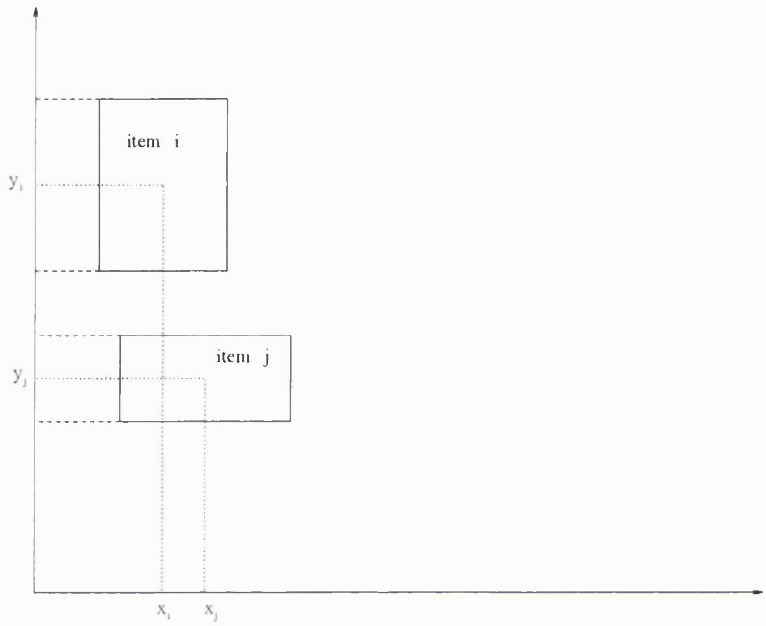

Figure 3.2: Avoiding equipment overlapping (y- direction)

If constraint (3.9) is active then :

$$E1_{ij} = 1, E2_{ij} = 0$$

If constraint (3.10) is active then :

$$E1_{ij} = 0, E2_{ij} = 1$$

If constraint (3.11) is active then :

$$E1_{ij} = 1, E2_{ij} = 1$$

In summary, the non-overlapping constraints included in the model are:

$$x_i - x_j + M(1 - Z_{ij} + E1_{ij} + E2_{ij}) \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (3.12)$$

$$x_j - x_i + M \cdot (2 - Z_{ij} - E1_{ij} + E2_{ij}) \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (3.13)$$

$$y_i - y_j + M \cdot (2 - Z_{ij} + E1_{ij} - E2_{ij}) \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (3.14)$$

$$y_j - y_i + M \cdot (3 - Z_{ij} - E1_{ij} - E2_{ij}) \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (3.15)$$

where M is an appropriate upper bound. Note that the above constraints are inactive for equipment items allocated to different floors (*i.e.* $Z_{ij} = 0$).

3.2.4 Distance Constraints

The single floor distance constraints presented in Papageorgiou and Rotstein (1998) are here extended for the multi-floor case:

$$R_{ij} - L_{ij} = x_i - x_j \qquad \forall\, (i,j) : f_{ij} = 1 \qquad (3.16)$$

$$A_{ij} - B_{ij} = y_i - y_j \qquad \forall\, (i,j) : f_{ij} = 1 \qquad (3.17)$$

$$U_{ij} - D_{ij} = H \cdot \sum_k k \cdot (V_{ik} - V_{jk}) \qquad \forall\, (i,j) : f_{ij} = 1 \qquad (3.18)$$

Thus, the total rectilinear distance between items i and j is given by:

$$TD_{ij} = R_{ij} + L_{ij} + A_{ij} + B_{ij} + U_{ij} + D_{ij} \qquad \forall\, (i,j) : f_{ij} = 1 \qquad (3.19)$$

3.2.5 Additional Layout Design Constraints

Lower bound constraints on the coordinates of the geometrical centre are included in order to avoid intersection of items with the origin of axes:

$$x_i \geq \frac{l_i}{2} \qquad \forall\, i \tag{3.20}$$

$$y_i \geq \frac{d_i}{2} \qquad \forall\, i \tag{3.21}$$

A rectangular shape of land area is assumed to be used and its dimensions are determined by:

$$x_i + \frac{l_i}{2} \leq X^{max} \qquad \forall\, i \tag{3.22}$$

$$y_i + \frac{d_i}{2} \leq Y^{max} \qquad \forall\, i \tag{3.23}$$

These dimensions are then used to calculate the land area, FA:

$$FA = X^{max} \cdot Y^{max} \tag{3.24}$$

3.2.6 Objective Function

The objective function of the simultaneous model includes:

- Connectivity cost:

$$\sum_{i} \sum_{j \neq i | f_{ij}=1} C_{ij}^{c} \cdot TD_{ij}$$

- Vertical pumping cost:

$$\sum_{i} \sum_{j \neq i | f_{ij}=1} C_{ij}^{v} \cdot D_{ij}$$

- Horizontal pumping cost:

$$\sum_{i} \sum_{j \neq i | f_{ij}=1} C_{ij}^{h} \cdot (R_{ij} + L_{ij} + A_{ij} + B_{ij})$$

- Floor construction cost:

$$FC1 \cdot NF + FC2 \cdot NF \cdot FA$$

- Land area cost:

$$LC \cdot FA$$

Overall, the problem is summarised as follows:

[Problem PO]

$$min \qquad \sum_{i} \sum_{j \neq i | f_{ij}=1} [C_{ij}^{c} \cdot TD_{ij} + C_{ij}^{v} \cdot D_{ij} + C_{ij}^{h} \cdot (R_{ij} + L_{ij} + A_{ij} + B_{ij})]$$

$$+FC1 \cdot NF + FC2 \cdot NF \cdot FA + LC \cdot FA$$

subject to constraints (3.1) - (3.7) and (3.12) - (3.24).

The above problem is an MINLP model because of the non-linearities involved in the last two terms of the objective function and in equation (3.24). However, the X^{max}, Y^{max} variables required for the calculations of FA can be approximated similarly to the work presented in Georgiadis *et al.* (1999). The value of land area,

FA, will be chosen from a set of S candidate rectangular area sizes, AR_s, with $\overline{X}_s$ and $\overline{Y}_s$ dimensions. Then, binary variables, Q_s, are introduced together with the constraints:

$$FA = \sum_s AR_s \cdot Q_s \tag{3.25}$$

$$\sum_s Q_s = 1 \tag{3.26}$$

The values of X^{max} and Y^{max} variables are forced to coincide with the dimensions of the selected area size:

$$X^{max} = \sum_s \overline{X}_s \cdot Q_s \tag{3.27}$$

$$Y^{max} = \sum_s \overline{Y}_s \cdot Q_s \tag{3.28}$$

By introducing the above approximation, the last two nonlinear terms of the objective function now result in bilinear and linear terms, respectively. The penultimate bilinear term can easily be linearised by introducing new continuous variables, $\overline{NQ}_s$:

$$\overline{NQ}_s \equiv NF \cdot Q_s \qquad \forall\, s$$

defined by:

$$\overline{NQ}_s \leq K \cdot Q_s \qquad \forall\, s \tag{3.29}$$

$$NF = \sum_s \overline{NQ}_s \tag{3.30}$$

Finally, the linearised problem corresponds to an MILP model which can be summarised as follows:

[Problem P]

$$min \quad \sum_i \sum_{j \neq i | f_{ij}=1} [C^c_{ij} \cdot TD_{ij} + C^v_{ij} \cdot D_{ij} + C^h_{ij} \cdot (R_{ij} + L_{ij} + A_{ij} + B_{ij})]$$

$$+FC1 \cdot NF + FC2 \cdot \sum_s AR_s \cdot \overline{NQ}_s + LC \cdot FA$$

subject to

constraints (3.1) - (3.7), (3.12) - (3.23) and (3.25) - (3.30).

All continuous variables in the formulation are defined as non-negative.

Next, a number of illustrative examples are presented to demonstrate the applicability of the MILP model [Problem P].

3.3 Computational Results

In this section, the proposed formulation is applied to a number of previously published examples of process plant layout optimisation. All examples were modelled using the GAMS modelling system (Brooke et al., 1998) coupled with the ILOG CPLEX V6.5 MILP optimisation package (1999). All the computational experiments were performed on an IBM RS6000 with a 5% margin of optimality. Five alternative sizes per dimension have been used in all examples thus leading to 25

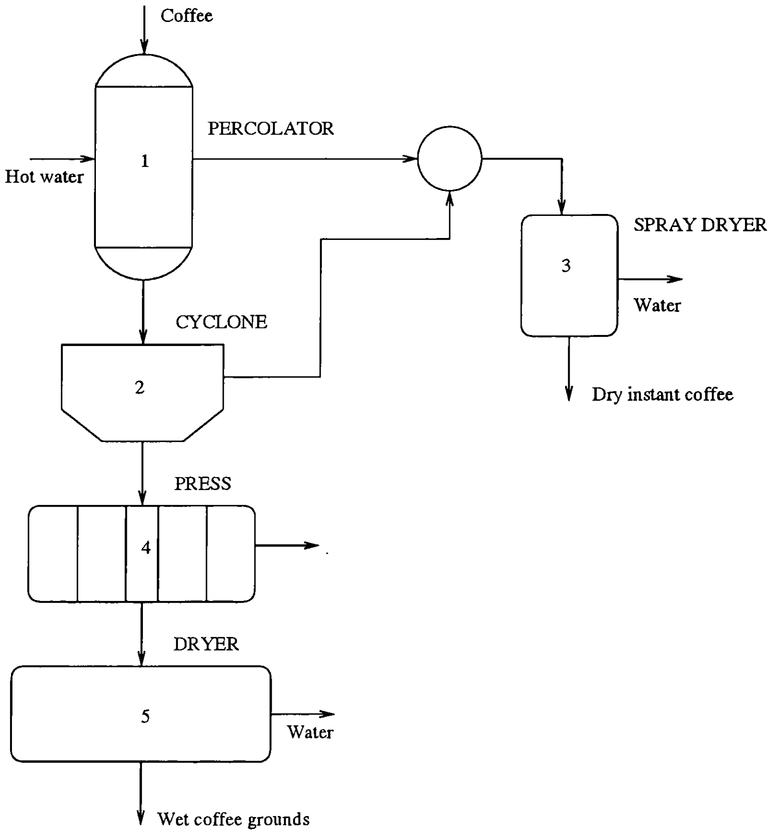

Figure 3.3: Flowsheet for coffee plant

candidate area sizes. It is also assumed here that construction dimensions (X^{max} and Y^{max}) are available in multiples of 10 m. A floor height of $5m$ is selected for all examples.

3.3.1 Instant Coffee Plant

The first example studied, is the 5-unit instant coffee plant (see Figure 3.3), introduced by Jayakumar and Reklaitis (1996). Three potential floors are assumed to be initially available.

The equipment dimensions are given in Table 3.1. Connection and pumping cost data are given in Table 3.2. The floor construction cost parameters, $FC1$ and $FC2$, are 3330 rmu and 66.7 rmu/m^2, respectively, and the land cost parameter, LC, is 66.7 rmu/m^2.

Table 3.1: Equipment dimensions for coffee plant

Unit	1	2	3	4	5
α_i $[m]$	15.8	3.2	15.8	6.3	9.5
β_i $[m]$	3.2	3.2	3.2	6.3	3.2

Table 3.2: Connection and pumping costs for coffee plant

Connection	C^c_{ij} $[rmu/m]$	C^h_{ij} $[rmu/m]$	C^v_{ij} $[rmu/m]$
(1,2)	600	2525	25250
(1,3)	800	3783	37830
(2,3)	350	631	6310
(2,4)	400	1879	18790
(4,5)	500	1420	14200

The resulting mathematical model includes 211 constraints, 64 integer and 74 continuous variables while the optimal layout is shown in Figure 3.4. The optimal solution (equipment orientation and location, equipment-floor allocation) is given in Table 3.3. As it can be seen, only gravity is utilised for the material transfer from unit 1 to 3 and 4 to 5. Also gravity is used for the vertical material transfer

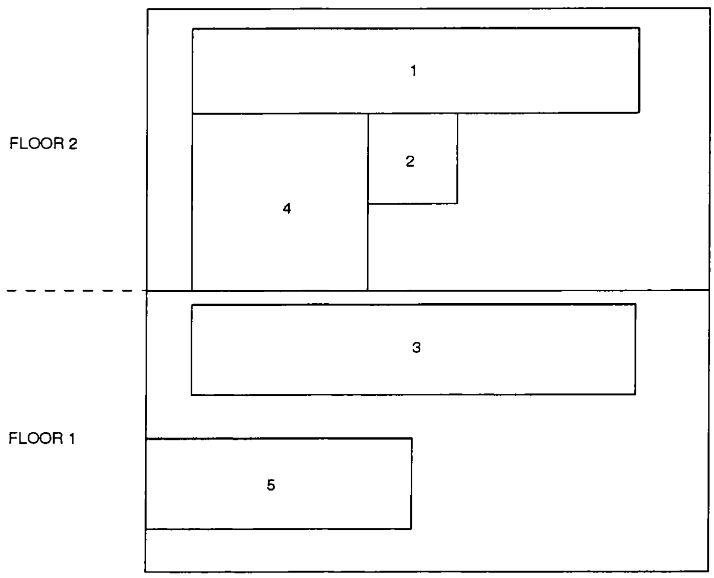

Figure 3.4: Optimal layout for coffee plant - Simultaneous approach

from unit 2 to 3. It should be noted that two out of the three initially available floors have finally been chosen. The total plant layout cost is 82366 *rmu* with the following breakdown: 16.8% for connection cost; 26.6% for horizontal and vertical pumping costs, 16.17% for land and 40.43% for floor construction cost. The optimal land area is 200 m^2 ($X^{max} = 20\ m$, $Y^{max} = 10\ m$). The corresponding CPU time is 3.1 s.

Next, the importance of considering the number of floors together with other layout decisions (*e.g.* orientation, location) within the same optimisation framework is illustrated. First, the number of floors is assumed to be fixed and then the reduced MILP model is solved[2]. For the single-floor case (*i.e.* *NF=1*), a suboptimal solution of 107497 *rmu* is obtained. This solution is 30.5% higher than the two-floor

[2]For these runs the margin of optimality used is 0.1%

Table 3.3: Optimal solution for coffee plant - Simultaneous approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	15.80	3.20	9.50	7.90	2
2	3.20	3.20	9.50	4.70	2
3	15.80	3.20	9.50	7.90	1
4	6.30	6.30	4.75	3.15	2
5	9.50	3.20	4.75	3.15	1

optimal solution of 82366 *rmu*. Moreover, the three-floor optimal plant layout has an objective function of 89343 *rmu* which is also suboptimal (8.5% higher than the optimal value).

The cost breakdown for the single-floor case is: 10.3% for connection cost; 37.2% for horizontal and vertical pumping costs, 24.7% for land and 27.8% for floor construction cost. Comparing the above breakdown with the optimal one, it is obvious that there is a significant increase in operating costs as gravity is not utilised any more for material transfer. Land cost is also increased as there is a need for a bigger land area to allocate all items on the same floor. On the other hand, floor construction cost is significantly decreased as less floors are required. It is worth mentioning that the three-floor optimal layout is cheaper than the single-floor one showing the savings potential of the multifloor allocation.

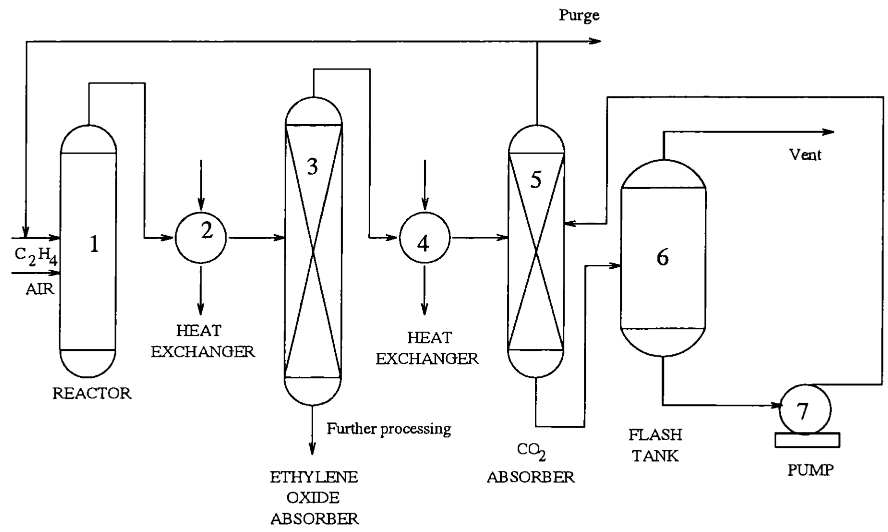

Figure 3.5: Flowsheet for ethylene oxide plant

3.3.2 Ethylene Oxide Plant

Consider the ethylene oxide plant, derived from the case study presented by Penteado and Ciric (1996). The plant flowsheet includes 7 units as shown in Figure 3.5. The equipment dimensions and the connection and pumping cost data are given in Tables 3.4 and 3.5, respectively. The $FC1$ and $FC2$ floor construction cost parameters, are 3330 rmu and 6.7 rmu/m^2, respectively, and the land cost parameter, LC, is 26.6 rmu/m^2. Three potential floors are assumed to be available.

Table 3.4: Equipment dimensions for ethylene oxide plant

Unit	1	2	3	4	5	6	7
α_i $[m]$	5.22	11.42	7.68	8.48	7.68	2.60	2.40
β_i $[m]$	5.22	11.42	7.68	8.48	7.68	2.60	2.40

Table 3.5: Connection and pumping costs for ethylene oxide plant

Connection	C^c_{ij} $[rmu/m]$	C^h_{ij} $[rmu/m]$	C^v_{ij} $[rmu/m]$
(1,2)	200	400	4000
(2,3)	200	400	4000
(3,4)	200	300	3000
(4,5)	200	300	3000
(5,1)	200	100	1000
(5,6)	200	200	2000
(6,7)	200	150	1500
(7,5)	200	150	1500

The resulting mathematical model includes 382 constraints, 100 integer and 103 continuous variables and is solved in 174 s. The optimal layout is shown in Figure 3.6 comprising two floors. Equipment orientation and location and equipment-floor allocation are given in Table 3.6. The total plant layout cost is 50817 rmu with the following breakdown: 23% for connection cost; 32.5% for horizontal and vertical pumping costs and 44.5% for land and construction costs. The optimal land area is 400 m^2 ($X^{max} = 20\ m$, $Y^{max} = 20\ m$).

As mentioned earlier, 25 ($10m \times 10m$) candidate area sizes have been used for all examples. A finer discretisation of the land area into 100 ($5m \times 5m$) candidate areas will give a solution of 50137 rmu as the land area is reduced to 375 m^2. An even finer discretisation with 625 ($2m \times 2m$) candidate areas will further reduce the

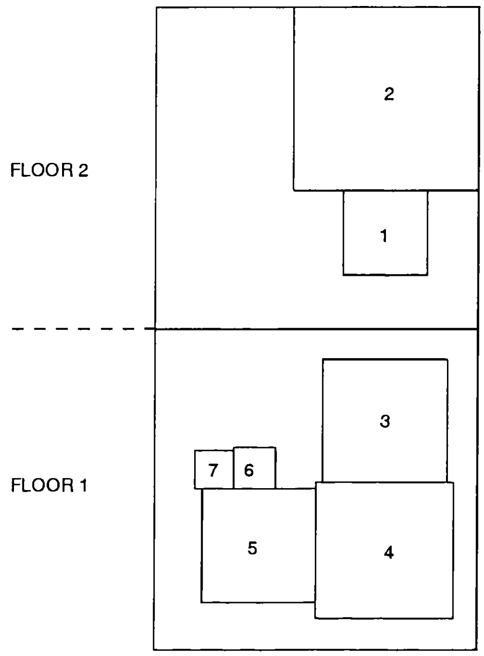

Figure 3.6: Optimal layout for ethylene oxide plant - Simultaneous approach

optimal solution by 5.9% to 47797 *rmu*. From the above values, it can be concluded that there is a significant effect of the land area discretisation on the total plant layout cost.

3.3.3 Batch Plant

This example was first proposed by Georgiadis *et al.* (1997). It considers the layout for an 11-unit batch plant (see Figure 3.7). The problem data are presented in Tables 3.7 and 3.8. Floor construction cost parameters, $FC1$ and $FC2$, are 3330 rmu and 3.33 rmu/m^2, respectively, and the land cost parameter, LC, is 66.6 rmu/m^2. The problem is solved in 4213 s and the optimal solution is presented in Table 3.9 and Figure 3.8. Connection cost represents 26.3%, pumping cost 26.9 % and land

Table 3.6: Optimal solution for ethylene oxide plant - Simultaneous approach

	Orientation		Location		Allocation
Equipment	l_i [m]	d_i [m]	x_i [m]	y_i [m]	Floor
1·	5.22	5.22	14.29	5.97	2
2	11.42	11.42	14.29	14.29	2
3	7.68	7.68	14.29	14.29	1
4	8.48	8.48	14.29	6.21	1
5	7.68	7.68	6.21	6.21	1
6	2.60	2.60	6.21	11.35	1
7	2.40	2.40	3.71	11.25	1

and construction cost 46.8 % of the total plant layout cost (37770 rmu). It should be noted that three out of five potential floors have finally been chosen with an area of 100 m^2 ($X^{max} = 10\ m$, $Y^{max} = 10\ m$) for each floor. The size of the model has significantly increased from the previous 7-unit example as shown in Table 3.13.

Table 3.7: Equipment dimensions for batch plant

Unit	V1	V2	1a	1b	2a	R2	R4	V5	V6	V5a	V6a
α_i [m]	5.0	6.0	4.0	6.5	6.0	4.0	4.0	5.0	4.0	2.0	3.0
β_i [m]	3.0	5.0	6.0	5.0	3.0	5.5	5.0	3.0	6.0	1.0	2.0

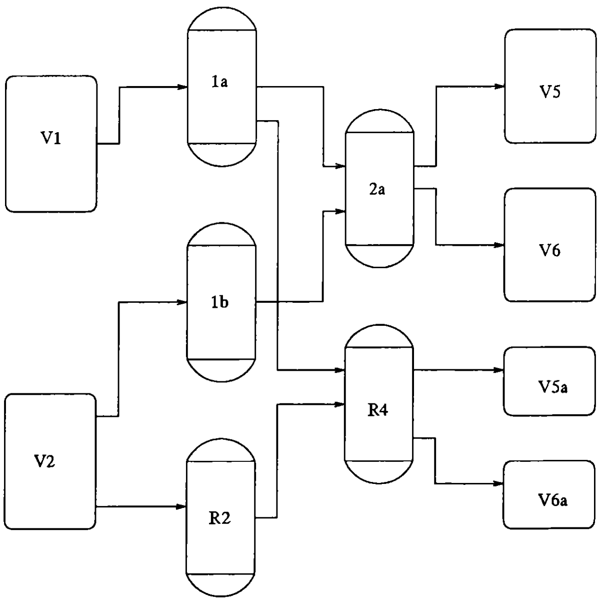

Figure 3.7: Flowsheet for batch plant

3.3.4 Cosmetic-grade Isopropyl Alcohol Plant

This example was first presented in Jayakumar and Reklaitis (1994) and considers the layout design for a 12-unit plant (see Figure 3.9) manufacturing cosmetic-grade isopropyl alcohol. The equipment dimensions are given in Table 3.10. Connection and pumping cost data are given in Table 3.11. The floor construction cost parameters, $FC1$ and $FC2$, are 2331 *rmu* and 9.9 rmu/m^2, respectively, and the land cost parameter, LC, is 133.2 rmu/m^2. Four potential floors are initially available.

The simultaneous approach appears incapable of solving this example to optimality. However an integer feasible solution was obtained with an objective function value of 111074 *rmu* (gap of 25.9%) after 10000 *s* as shown in Tables 3.12. In order to overcome the above difficulty, a new solution approach should be investigated which

Table 3.8: Connection and pumping costs for batch plant

Connection	C^c_{ij} $[rmu/m]$	C^h_{ij} $[rmu/m]$	C^v_{ij} $[rmu/m]$
(V1,1a)	160	950	9500
(V2,1b)	160	380	3800
(V2,R2)	160	570	5700
(1a,2a)	160	570	5700
(1a,R4)	160	190	1900
(1b,2a)	160	285	2850
(R2,R4)	160	456	4560
(2a,V5)	160	456	4560
(2a,V6)	160	304	3040
(R4,V5a)	160	285	2850
(R4,V6a)	160	285	2850

is capable of tackling flowsheets larger than 11 units.

3.4 Concluding Remarks

In this chapter, a simultaneous approach for the optimal multi-floor process plant layout problem has been considered. A general mathematical framework has been described, which determines simultaneously the number of floors, land area, optimal equipment-floor allocation and equipment location (*i.e.* coordinates and orientation)

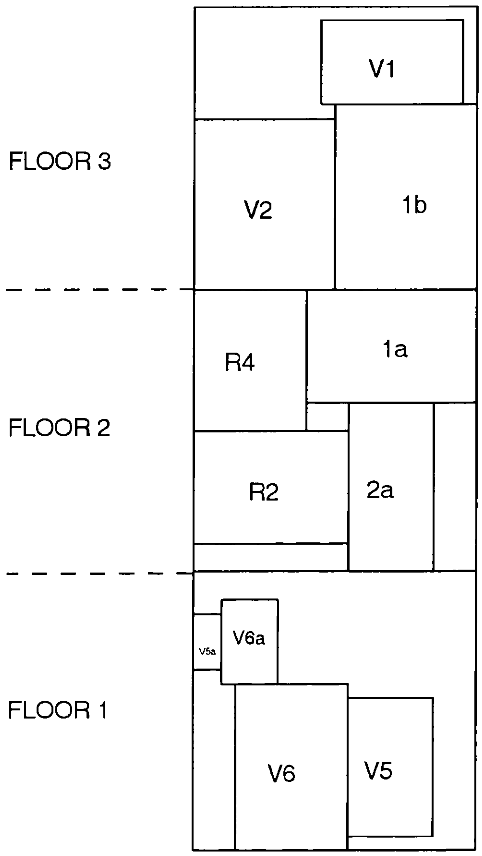

Figure 3.8: Optimal layout for batch plant - Simultaneous approach

so as to minimise the total plant layout cost. The resulting optimisation problem corresponds to an MILP model. The applicability of the proposed model has been demonstrated by four illustrative examples. As discussed earlier, there is a trade-off between operating/land cost and floor construction cost which determines the optimal number of floors and equipment layout.

A summary of the optimal objective function values and the corresponding CPU times for the four examples studied are shown in Table 3.12. The respective model sizes (number of equations and integer and continuous variable) are presented in

Table 3.9: Optimal solution for batch plant - Simultaneous approach

	Orientation		Location		Allocation
Equipment	l_i [m]	d_i [m]	x_i [m]	y_i [m]	Floor
V1	5	3	7.00	8.00	3
V2	5	6	2.50	3.00	3
1a	6	4	7.00	8.00	2
1b	5	6.5	7.50	3.25	3
2a	3	6	7.00	3.00	2
R2	5.5	4	2.75	3.00	2
R4	4	5	2.00	7.50	2
V5	3	5	7.00	3.00	1
V6	4	6	3.50	3.00	1
V5a	1	2	0.50	7.50	1
V6a	2	3	2.00	7.50	1

Table 3.13. It is clear from the above tables that there is a significant increase of CPU time with the example size and the connectivity. In the case of flowsheets with more than 11-units the resulting model renders is difficult to solve. Therefore, the need for the development of efficient solution procedures for the multifloor process plant layout is evident and will be investigated in the next two chapters.

Table 3.10: Dimensions of equipment items for isopropyl alcohol plant

Unit	1	2	3	4	5	6	7	8	9	10	11	12
α_i $[m]$	6.0	7.2	6.0	4.8	4.8	6.0	4.8	7.2	4.8	7.2	6.0	7.2
β_i $[m]$	4.8	6.0	7.2	6.0	6.0	4.8	6.0	4.8	6.0	6.0	4.8	4.8

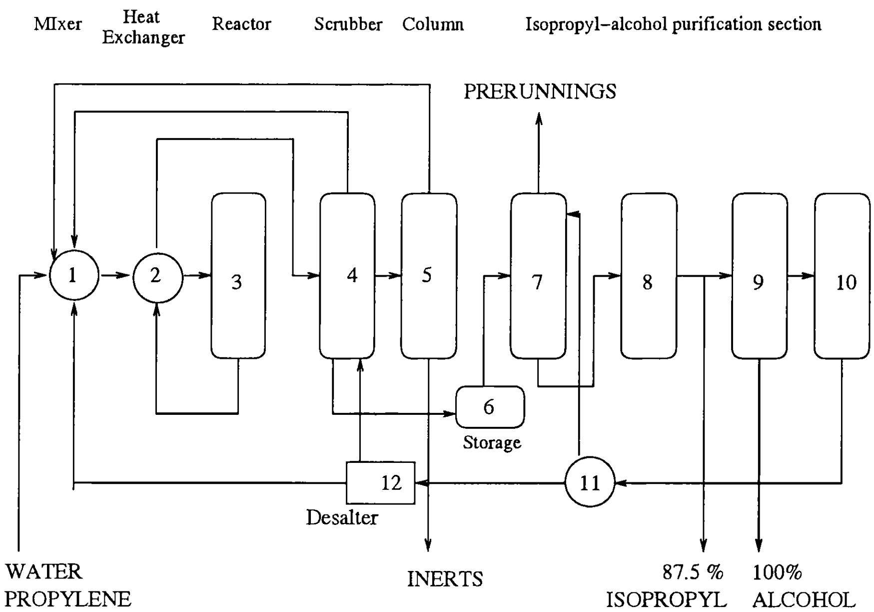

Figure 3.9: Flowsheet for isopropyl alcohol plant

Table 3.11: Connection and pumping costs for isopropyl alcohol plant

Connection	C^c_{ij} $[rmu/m]$	C^h_{ij} $[rmu/m]$	C^v_{ij} $[rmu/m]$
(1,2)	120.0	939	9390
(2,3)	195.0	789	7890
(2,4)	135.0	909	9090
(3,2)	195.0	789	7890
(4,1)	12.0	42	420
(4,5)	45.0	210	2100
(4,6)	135.0	669	6690
(5,1)	42.0	168	1680
(6,7)	135.0	669	6690
(7,8)	165.0	540	5400
(8,9)	90.0	570	5700
(8,11)	24.0	72	720
(9,10)	90.0	420	4200
(10,11)	24.0	72	720
(11,7)	13.5	33	330
(11,12)	36.0	108	1080
(12,1)	12.0	42	420
(12,4)	27.0	66	660

Table 3.12: Objective function values in *rmu*

	Approach	
Example	Objective	CPU time
coffee plant	82366	3.1
ethylene oxide plant	50817	174
batch plant	37770	4213
isopropyl alcohol plant	111074	10000.0 *

* Computational limit of 10000 s is used

Table 3.13: Model sizes

			Variables	
Example	Units	Constraints	Integer	Continuous
coffee plant	5	211	64	74
ethylene oxide plant	7	382	100	103
batch plant	11	1198	247	146
isopropyl alcohol plant	12	1241	274	186

Chapter 4

Multifloor Process Plant Layout - A Decomposition Approach

In the previous chapter, a simultaneous approach for the multi-floor process plant layout problem has been presented using a general mathematical programming formulation which determines simultaneously the number of floors, land area, floor allocation of each equipment item and detailed layout for each floor. The overall problem was formulated as an MILP model based on a continuous domain representation.

The simultaneous approach has proven capable of solving flowsheets up to 11-units. However, in the case of larger flowsheets, the size of the model increases and the problem becomes difficult to solve. Therefore, efficient solution procedures for the multi-floor process plant layout problem are required.

In this chapter, we investigate a decomposition approach suitable for larger flowsheets without compromising significantly the solution quality. To reduce the size of the model, a decomposition approach is proposed where smaller problems, a master and a subproblem, are solved iteratively until convergence with a given tolerance. The master problem determines the number of floors and the allocation of units to floors and the subproblem the detailed layout of each floor. The problem and the basic assumptions remain the same as stated in section 3.1.

Next, the decomposition solution approach is described in detail while its applicability is demonstrated through a number of illustrative examples.

4.1 A Decomposition Solution Approach

In addition to the indices, parameters and variables associated with the layout problem introduced in section 3.2, the following notation is used:

Parameters

δ_{ij} connection and horizontal pumping cost approximation parameter $[rmu]$

λ_{rik} relevant equipment resource utilisation

FA^{max} maximum value of continuous variable FA in Master problem $[m^2]$

S_i footprint area of item i $[m^2]$

Γ maximum number of units per floor

Λ_{rk} availability level on resource r for floor k

Binary Variables

W_k 1 if floor k is occupied; 0 otherwise

Continuous Variables

$\overline{WFA}_k$ linearisation variable expressing the product of W_k and FA $[m^2]$

In this section, a decomposition solution procedure for the multi-floor process plant layout problem is proposed. The approach comprises a master problem and a subproblem.

The master problem provides a lower bound to the optimal solution of the original problem. The number of floors and the allocation of units to floors are determined by the master problem. Then, the solution of the subproblem provides an upper bound to the optimal solution of the original problem and determines the detailed layout for every floor. The master problem and the subproblem are solved iteratively until convergence (crossover of upper and lower bounds), with an acceptable tolerance.

4.1.1 Master Problem

The master problem determines the optimal number of floors as well as equipment-floor assignment. An approximation of the original objective function is used including an approximation of the connection and the pumping costs based on minimum rectilinear distances and the land and floor construction costs. The feasible region of the master problem essentially constitutes a relaxation of that of the original simultaneous problem [P] as some constraints are left out or approximated thus providing a valid lower bound. In particular, the orientation (constraints (3.6) - (3.7)), non-overlapping (constraints (3.12) - (3.15)), horizontal distance (constraints (3.16) -

(3.17)) and additional layout constraints (constraints (3.20) - (3.23)) are omitted while an approximation of the area constraints is used. Next, the mathematical model of the master problem is described in detail.

Floor Constraints

Constraints (3.1) - (3.5) are used as described in section 3.2.1. New integer constraints are included in the model to relate the number of floors, NF, with the new binary variables, W_k;

$$NF = \sum_k W_k \tag{4.1}$$

A floor can be occupied only if the previous floor is occupied:

$$W_k \leq W_{k-1} \qquad \forall\, k = 2..K \tag{4.2}$$

A unit can only be allocated to a floor if that floor exists ($i.e$ $W_k = 1$):

$$V_{ik} \leq W_k \qquad \forall\, i, k \tag{4.3}$$

It should be noted that if one floor does not exist ($i.e.$ $W_k = 0$) then constraints (4.3) do not allow any equipment item to be allocated to floor k by forcing the associated V_{ik} variables to zero.

Also, if floor k exists ($i.e.$ $W_k = 1$), then at least one equipment item should be allocated to it:

$$\sum_i V_{ik} \geq W_k \qquad \forall\ k \tag{4.4}$$

In addition, each floor may comprise up to a maximum number of units (Γ) in order to simplify the operational complexity of each floor:

$$\sum_i V_{ik} \leq \Gamma \cdot W_k \qquad \forall\ k \tag{4.5}$$

The above constraints can further be generalised to take into account of limited availability of resources as follows:

$$\sum_i \lambda_{rik} \cdot V_{ik} \leq \Lambda_{rk} \cdot W_k \qquad \forall\ r, k \tag{4.6}$$

Vertical Distance Constraints

Vertical distances between equipment items are determined by constraints (3.18). Also, minimum horizontal distances are used for approximating horizontal, connection and pumping costs in the objective function.

Area Constraints

The total floor area is always larger than the summation of the footprint areas of the units allocated to that floor:

$$FA \geq \sum_i S_i \cdot V_{ik} \qquad \forall\ k \tag{4.7}$$

In addition, constraints (3.25)- (3.26) (see section 3.2.6) are used.

Objective Function

The objective function to be minimised includes

- An approximation of the connection and (horizontal and vertical) pumping costs by using the same cost factors as in the simultaneous model but for the minimum possible horizontal distances:

$$\sum_i \sum_{j \neq i | f_{ij}=1} \delta_{ij} \cdot Z_{ij} + C^c_{ij} \cdot U_{ij} + (C^c_{ij} + C^v_{ij}) \cdot D_{ij}$$

where parameter δ_{ij} is given by:

$$\delta_{ij} = (C^c_{ij} + C^h_{ij}) \cdot \frac{min(a_i, b_i) + min(a_j, b_j)}{2}$$

- Floor construction cost:

$$FC1 \cdot NF + FC2 \cdot \sum_k W_k \cdot FA$$

- Land area cost:

$$LC \cdot FA$$

Overall, the master problem can be summarised as follows:

[*Problem MO*]

$$\begin{aligned} min \qquad & \sum_i \sum_{j \neq i | f_{ij}=1} \delta_{ij} \cdot Z_{ij} + C^c_{ij} \cdot U_{ij} + (C^c_{ij} + C^v_{ij}) \cdot D_{ij} \\ & + FC1 \cdot NF + FC2 \cdot \sum_k W_k \cdot FA + LC \cdot FA \end{aligned}$$

subject to constraints (4.1) - (4.7) and

part of chapter 3 constraints [(3.1) - (3.5), (3.18) and (3.25) - (3.26)].

All continuous variables in the formulation are defined as non-negative.

The above problem is an MINLP model because of the bi-linearities involved in the penultimate term of the objective function, which can easily be linearised by introducing new continuous variables, $\overline{WFA}_k$;

$$\overline{WFA}_k \equiv W_k \cdot FA \qquad \forall\, k$$

defined by:

$$\overline{WFA}_k \leq FA^{max} \cdot W_k \qquad \forall\, k \tag{4.8}$$

$$\overline{WFA}_k \geq FA - FA^{max} \cdot (1 - W_k) \qquad \forall\, k \tag{4.9}$$

where FA^{max} is given by:

$$FA^{max} = \sum_i S_i$$

Finally, the linearised problem corresponds to the following MILP model:

[*Problem MR*]

$$\begin{aligned} min \qquad & \sum_i \sum_{j \neq i | f_{ij}=1} \delta_{ij} \cdot Z_{ij} + C^v_{ij} \cdot D_{ij} + C^c_{ij} \cdot U_{ij} + (C^c_{ij} + C^v_{ij}) \cdot D_{ij} \\ & \qquad + FC1 \cdot NF + FC2 \cdot \sum_k \overline{WFA}_k + LC \cdot FA \end{aligned}$$

subject to constraints (4.1) - (4.9) and

part of chapter 3 constraints [(3.1) - (3.5), (3.18) and (3.25) - (3.26)].

It is clear that the solution of $[MR]$ provides a lower bound to the solution of the original problem $[P]$ (presented in chapter 3) as the feasible region of $[MR]$ is simply a relaxation of $[P]$ while the objective function constitutes an under-estimator for the original objective function.

4.1.2 Subproblem Model

A reduced simultaneous model is used as subproblem. In our case, the number of floors, and the allocation of units to floor are given by the solution of the master problem. The number of floors, NF, will now be treated as a parameter according to the solution of the master problem. As the assignment of equipment items to floors is part of the master problem, all floor constraints (3.1) - (3.5) can be omitted from the model. Similarly, the Z_{ij} variables are not necessary and can be treated as parameters, while the non-overlapping constraints are only defined for units assigned to the same floor. Moreover, vertical distances between units are now known from the master problem and can be treated as parameters in the subproblem model.
Note that as the number of floors is now a parameter, construction cost is not anymore a nonlinear term in the objective function and therefore linearisation constraints (3.29) and (3.30) are not required in the model anymore.
In summary, the complete subproblem can now be stated as:

[Problem S]

$$min \quad \sum_{i} \sum_{i \neq j | f_{ij}=1} [C^c_{ij} \cdot TD_{ij} + C^v_{ij} \cdot D_{ij} + C^h_{ij} \cdot (R_{ij} + L_{ij} + A_{ij} + B_{ij})]$$

$$+FC1 \cdot NF + FC2 \cdot NF \cdot FA + LC \cdot FA$$

subject to

- Part of chapter 3 constraints:
  - equipment orientation constraints(3.6) - (3.7);
  - distance constraints (3.16), (3.17) and (3.19);
  - additional layout constraints (3.20) - (3.23);
  - area constraints (3.25) - (3.28);
- non-overlapping constraints written only for equipment items assigned by the master problem to the same floor (*i.e.* $Z_{ij} = 1$):

$$x_i - x_j + M \cdot (E1_{ij} + E2_{ij}) \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (4.10)$$

$$x_j - x_i + M \cdot (1 - E1_{ij} + E2_{ij}) \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (4.11)$$

$$y_i - y_j + M \cdot (1 + E1_{ij} - E2_{ij}) \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (4.12)$$

$$y_j - y_i + M \cdot (2 - E1_{ij} - E2_{ij}) \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1..N-1, j = i+1..N \quad (4.13)$$

The above problem [S] corresponds to an MILP model. As problem [S] constitutes a reduced version of the original problem [P], the solution of [S] will provide a valid upper bound on the solution of [P].

4.1.3 Decomposition Solution Procedure

Here, a decomposition procedure is described by solving iteratively master problem [MR] and subproblem [S] until convergence. The following sets and parameters are defined for the description of the decomposition algorithm:

At every iteration, all previous integer solutions of the master problem are excluded. This can be achieved by introducing the following cut constraints in the master problem at iteration m:

$$\sum_{k \in U_w^m} W_k + \sum_{(i,k) \in U_v^m} V_{ik} - \sum_{k \in L_w^m} W_k - \sum_{(i,k) \in L_v^m} V_{ik} \leq |U_w^m| + |U_v^m| - 1 \tag{4.14}$$

where U_w^m and L_w^m denote the subsets of W_k variables that were at their upper and lower bounds respectively at the solution of the master problem at iteration m. In a similar way, U_v^m and L_v^m denote the subsets of V_{ik} variables at their upper and lower bounds respectively at the solution of the master problem at iteration m.

The algorithm will terminate when the current lower, Φ^L, and the best upper. $\Phi^{U,min}$, bound of the optimal solution Φ of the original problem objective function converge with a pre-specified tolerance ϵ or maximum number of iterations m^{max} has been exceeded. The optimal solution corresponds to the subproblem solution with the lowest objective function value provided that the problem is feasible.

The decomposition solution algorithm comprises the following steps:

[Algorithm D]

1. Set best feasible solution $\Phi^{U,min} = +\infty$. Initialise iterations counter; $m := 0$.

2. Set $m := m + 1$. If $m > m^{max}$ STOP.

3. Solve master problem $[MR]$ (including cuts (4.14)) and get Φ^L. If $[MR]$ is infeasible, STOP.

4. If $\frac{\Phi^{U,min} - \Phi^L}{\Phi^{U,min}} \leq \epsilon$, STOP.

5. Solve subproblem $[S]$ according to the solution of master problem $[MR]$ and get a valid upper bound Φ^U. If at any stage the subproblem is infeasible go to Step 2.

6. If $\Phi^U \leq \Phi^{U,min}$ keep current solution as the best feasible solution and set $\Phi^{U,min} := \Phi^U$.

7. If $\frac{\Phi^{U,min} - \Phi^L}{\Phi^{U,min}} \leq \epsilon$, STOP. Otherwise go to Step 2.

4.2 Computational Results

In this section, the proposed solution approach is applied to four examples. All examples were modelled using the GAMS modelling system coupled with the ILOG CPLEX V6.5 MILP optimisation package. All the computational experiments were performed on an IBM RS6000 with 1% margin of optimality for the master problem and the subproblem. The algorithms terminate when the current lower bound (current master problem solution) and the best upper bound (best subproblem solution) differ less than 5%. The results from Examples 1 and 2 are compared with those of the simultaneous approach, where a 5% margin of optimality was used to provide a measure of the solution quality obtained by both approaches. It should be added that the third example could not be solved to optimality with the simultaneous approach after a computational limit of 10000 s.

Again, the land area is chosen from a given set of alternative rectangular area sizes. Here, we use five alternative sizes for x and y directions, thus resulting in 25 candidate area sizes each of them being $10m \times 10m$. A floor height of $5m$ is used for all examples.

4.2.1 Instant Coffee Plant

The first example studied, is the 5-unit instant coffee plant (see Figure 3.3). The dimensions of equipment items, the connection and pumping costs and the floor and land cost parameters are all given in section 3.3.1. Three potential floors were initially assumed. The decomposition approach objective function values for the master and subproblem for each iteration are illustrated in Figure 4.1. The algorithm requires 12 iterations to converge while the optimal solution was obtained after 9 iterations. As shown in Table 4.6, both approaches result in the same objective function value. However, the decomposition approach requires half the CPU time of the simultaneous approach (see Table 4.7).

The optimal two-floor layout determined by the decomposition approach is shown in Figure 4.2. It is worth noting that the optimal layouts of both approaches (simultaneous and decomposition) are equivalent as each of them can easily be derived by an 180° rotation of the layout of each floor. The above degeneracy stems mainly

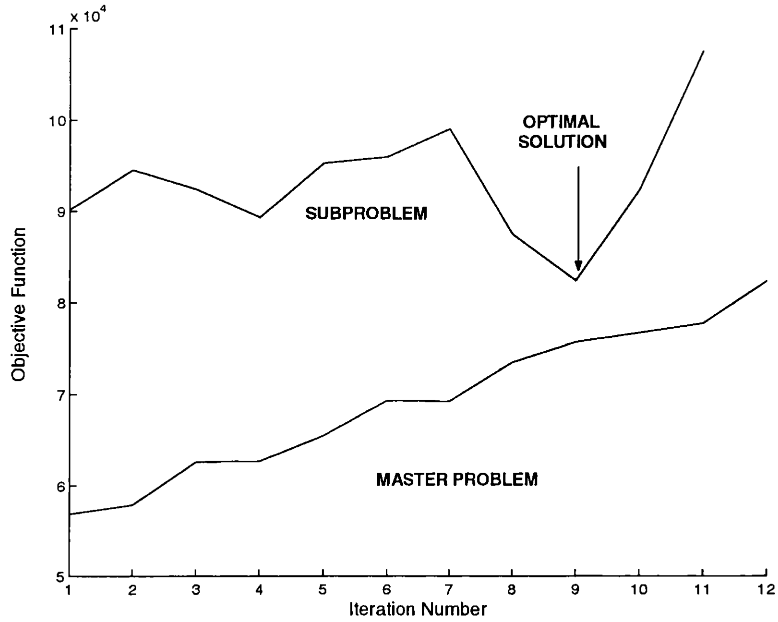

Figure 4.1: Convergence for decomposition approach for coffee process

from the discretisation of the land area. The optimal equipment orientation and location are given in Table 4.1.

4.2.2 Ethylene Oxide Plant

The second example considers the ethylene oxide plant (see Figure 3.5). All data have been presented in section 3.3.2. Both simultaneous and decomposition approaches obtain the same objective function (see Table 4.6). However, it is evident from Tables 3.6 and 4.2 and Figures 3.6 and 4.3. that degenerate optimal solutions were obtained with the same item-floor assignment but different location of equipment items. Both approaches select two out of the three initial floors in the final solution.

The decomposition approach solves the problem faster than the simultaneous ap-

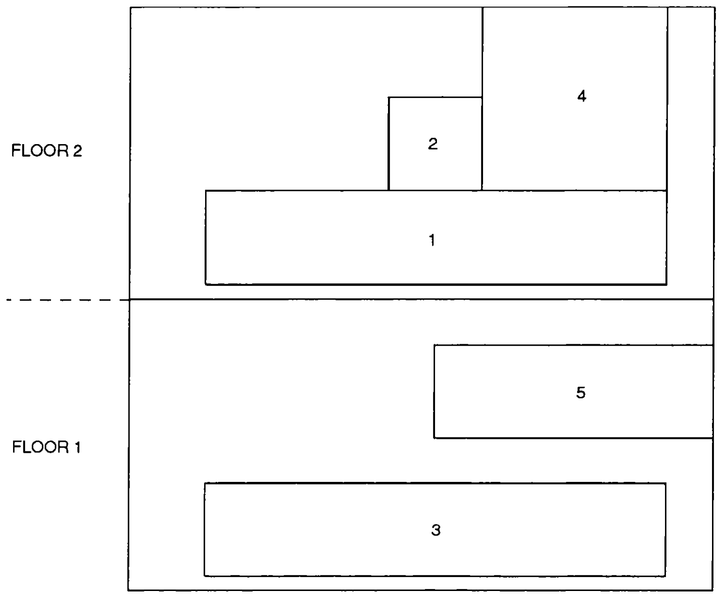

Figure 4.2: Optimal layout for coffee process - Decomposition approach

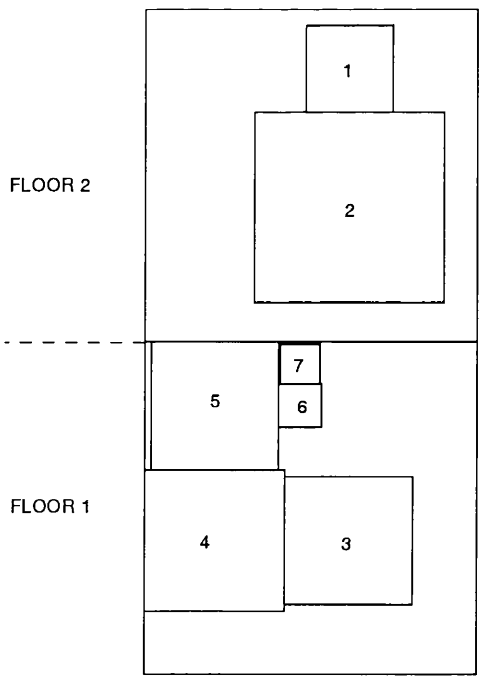

Figure 4.3: Optimal layout for ethylene oxide plant - Decomposition approach

Table 4.1: Optimal solution for coffee process - Decomposition approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	15.80	3.20	10.50	2.10	2
2	3.20	3.20	10.50	5.30	2
3	15.80	3.20	10.50	2.10	1
4	6.30	6.30	15.25	6.85	2
5	9.50	3.20	15.25	6.85	1

proach (see Table 4.7), thus illustrating the efficiency of this solution approach. Finally, the decomposition approach requires 11 iterations in total to converge with the second iteration obtaining the best solution as clearly depicted in Figure 4.4.

4.2.3 Cosmetic-Grade Isopropyl Alcohol Plant

This example considers the layout design for a 12-unit cosmetic-grade isopropyl alcohol plant (see Figure 3.9). The equipment dimensions and the connection, pumping, land and floor construction cost data have been given in section 3.3.4. Four potential floors are initially available. As mentioned earlier and also shown in Tables 4.6 and 4.7, the simultaneous approach cannot solve this example with a 5% margin of optimality in 10000 s. On the other hand, the decomposition approach solves the problem in 4457 s (see Table 4.7) and requires 40 iterations to converge as shown in Figure 4.5 while the twenty first iteration provides the optimal solution (101100

Table 4.2: Optimal solution for ethylene oxide plant - Decomposition approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	5.22	5.22	12.32	16.4	2
2	11.42	11.42	12.32	8.08	2
3	7.68	7.68	12.32	8.08	1
4	8.48	8.48	4.24	8.08	1
5	7.68	7.68	4.24	16.16	1
6	2.60	2.60	9.38	16.16	1
7	2.40	2.40	9.38	18.66	1

rmu). The optimal area is 200 m^2 per floor. The optimal layout details for the decomposition approach are presented in Figure 4.6 and Tables 4.3.

4.2.4 Maleik Anhydride Plant

This new example considers a 14-unit maleik anhydride process, based on a flowsheet presented in Meyers (1986). The simplified flowsheet is shown in Figure 4.7 while the equipment dimensions are given in Table 4.4. Connection and pumping cost data are given in Table 4.5. The floor construction cost parameters, $FC1$ and $FC2$, are 3330 rmu and 6.6 rmu/m^2, respectively, and the land cost parameter, LC, is 66.7 rmu/m^2.

It is clear from Tables 4.6 and 4.7 that both the simultaneous and decomposition

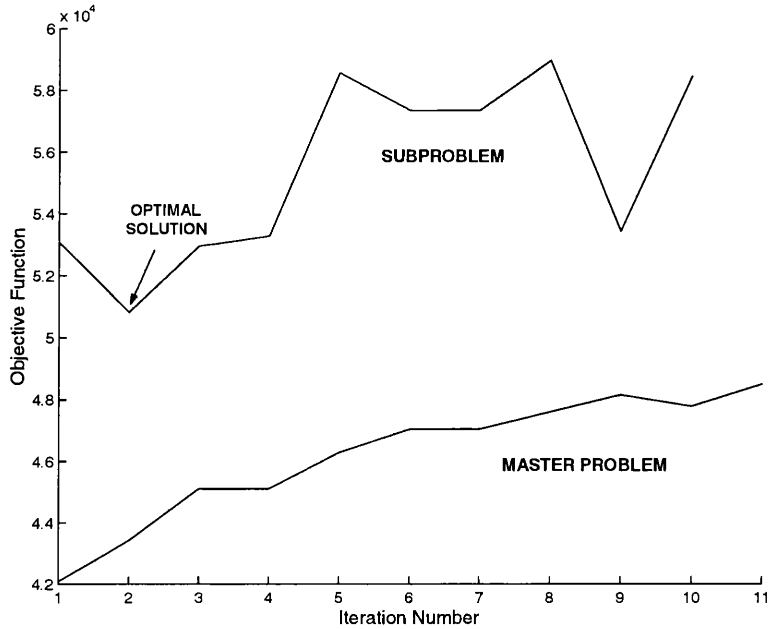

Figure 4.4: Convergence for decomposition approach for ethylene oxide plant

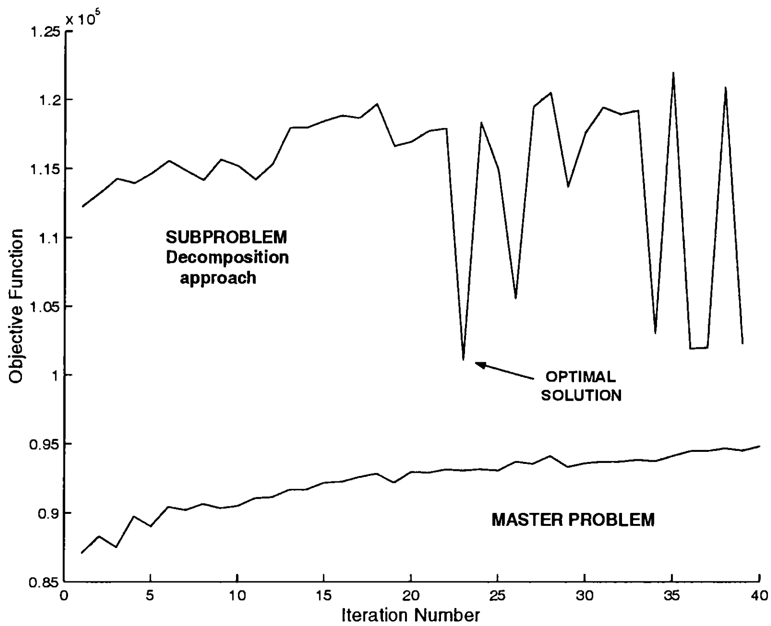

Figure 4.5: Convergence for decomposition approach for isopropyl alcohol plant

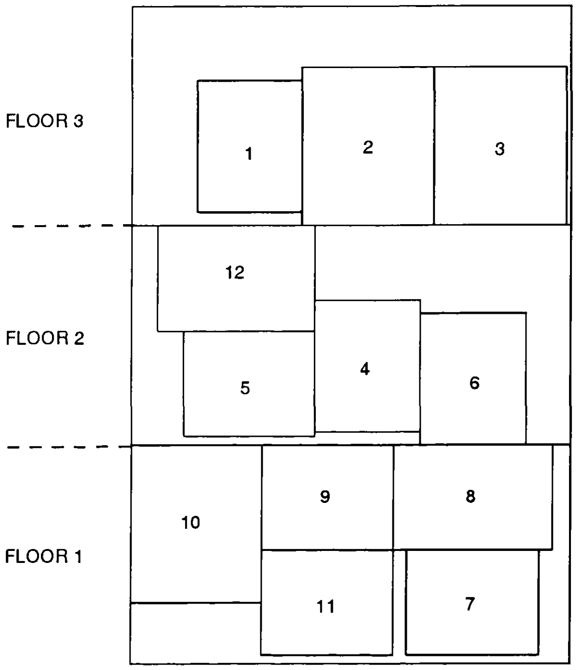

Figure 4.6: Optimal layout for isopropyl alcohol plant - Decomposition approach

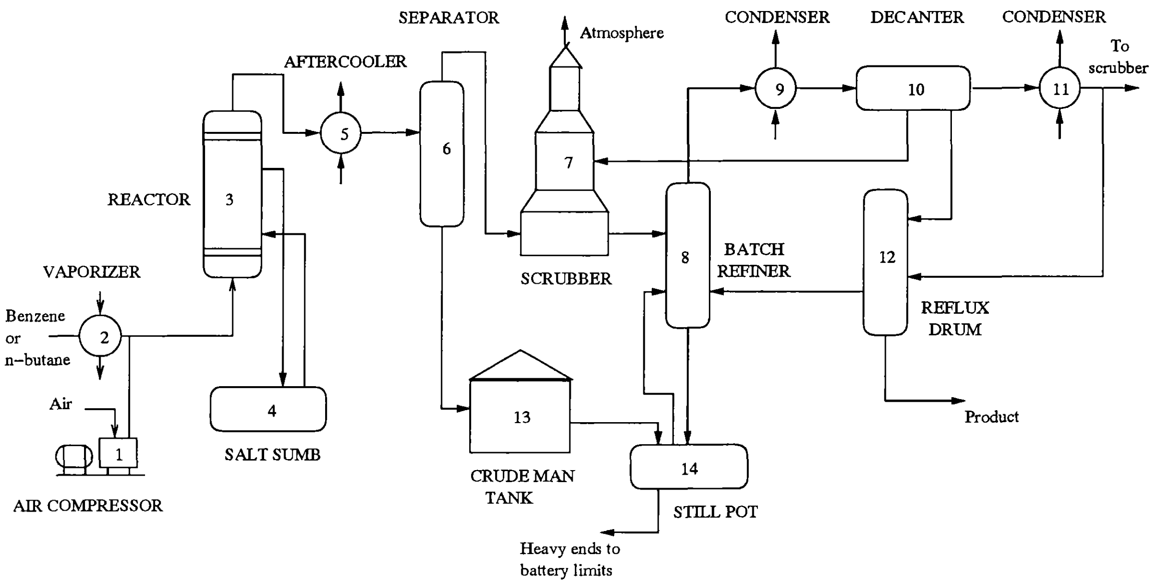

Figure 4.7: Flowsheet for maleik anhydride plant

approaches cannot solve this example within the pre-specified time limit of 10000 s and optimality margins for each approach. For the simultaneous approach, we get an objective function of 102335 rmu with a gap of 82.6%. For the decomposition approach, the subproblem of the first iteration cannot be solved for an optimality margin of 1% and an allocation of items to two floors (8 to the first one and 6 to the second). However, an integer feasible solution has been obtained of 53919 rmu exhibiting a gap of 32.4%.

4.3 Concluding Remarks

In this chapter, an improved solution approach for the optimal multi-floor process plant layout problem has been considered based on a decomposition solution scheme. The new approach determines the number of floors, land area, optimal equipment-floor allocation and equipment location (*i.e.* coordinates and orientation) so as to minimise the total plant layout cost. The applicability of the proposed approach has been demonstrated by four illustrative examples.

The proposed approach compares favourably with the simultaneous approach presented in chapter 3. As shown in Tables 4.6 and 4.7, the decomposition approach solves flowsheets of 5 and 7 units (instant coffee plant and ethylene oxide plant, respectively) much faster than the simultaneous approach.

Despite though the significant reduction of CPU times and the solution of larger examples (see section 4.2.3; 12-unit example) the decomposition approach still appears to have difficulties in tackling larger flowsheets (*e.g.* 14-unit, maleik anhydride plant). The main problem focuses on the solution of the subproblem especially when many units are allocated to the same floor (see section 4.2.4). In order to overcome this difficulty, an alternative approach should be considered for the solution of the subproblem which is investigated in the next chapter.

Table 4.3: Optimal solution for isopropyl alcohol plant - Decomposition approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	4.8	6.0	5.4	3.6	3
2	6.0	7.2	10.8	3.6	3
3	6.0	7.2	16.8	3.6	3
4	4.8	6.0	10.8	3.6	2
5	6.0	4.8	5.4	2.8	2
6	4.8	6.0	15.6	3.0	2
7	6.0	4.8	15.6	2.8	1
8	7.2	4.8	15.6	7.6	1
9	6.0	4.8	9.0	7.6	1
10	6.0	7.2	3.0	6.4	1
11	6.0	4.8	9.0	2.8	1
12	7.2	4.8	4.8	7.6	2

Table 4.4: Dimensions of equipment items for maleik anhydride plant

Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14
α_i $[m]$	3.0	2.5	4.0	3.0	2.5	4.0	4.5	3.5	3.0	3.0	2.0	4.0	3.5	2.5
β_i $[m]$	4.5	3.5	3.0	4.5	4.0	4.0	3.5	3.0	4.5	3.0	3.5	2.0	3.0	3.5

Table 4.5: Connection and pumping costs for maleik anhydride plant

Connection	C^c_{ij} $[rmu/m]$	C^h_{ij} $[rmu/m]$	C^v_{ij} $[rmu/m]$
(1,3)	150	300	3000
(2,3)	150	300	3000
(3,4)	50	100	1000
(3,5)	300	600	6000
(4,3)	50	100	1000
(5,6)	300	600	6000
(6,7)	250	500	5000
(6,13)	50	100	1000
(7,8)	280	560	5600
(8,9)	250	500	5000
(8,14)	80	160	1600
(9,10)	250	500	5000
(10,11)	150	300	3000
(10,12)	100	200	2000
(10,7)	30	60	600
(11,12)	150	300	3000
(12,8)	30	60	600
(13,14)	50	100	1000
(14,8)	20	40	400

Table 4.6: Objective function values in *rmu*

Example	Approach	
	Simultaneous	Decomposition
coffee plant	82366	82366
ethylene oxide plant	50817	50817
isopropyl alcohol plant	111074	101100
maleik anhydride plant	102335	53919

Table 4.7: CPU times in *s*

Example	Approach	
	Simultaneous	Decomposition
coffee plant	3.1	1.5
ethylene oxide plant	174.0	37.0
isopropyl alcohol plant	10000.0 *	4457.6
maleik anhydride plant	10000.0*	10000.0*

* Computational limit of 10000 *s* is used

Chapter 5

Multifloor Process Plant Layout - An Iterative Approach

In the last two chapters, two solution approaches for the multi-floor process plant layout problem have been presented. The first one is a simultaneous approach and the second one is a decomposition approach. Both approaches determine the number of floors, land area, floor allocation of each equipment item and detailed layout for each floor.

The simultaneous approach is capable of tackling flowsheets up to 11 unit. The decomposition approach, which comprises a master and a subproblem, can solve larger flowsheets (up to 12 units) in significant smaller CPU times. In an attempt to solve even larger examples, difficulties appear in the solution of the subproblem within 1% margin of optimality. For this reason, there is a need of a new approach for the solution of subproblem at each iteration.

In this chapter, a novel solution approach for the multi-floor process plant layout problem is presented based on an iterative solution scheme. The new approach comprises the same components as the decomposition approach (a master problem and a subproblem), which are solved iteratively until convergence. However, during each iteration a different algorithm is adopted for the solution of the subproblem. Next, the iterative solution approach is described.

5.1 An Iterative Solution Approach

In this section, an iterative solution approach is described, which uses the same models as the ones described in chapter 4 for the master problem and the subproblem. The main difference between the decomposition and iterative approaches is the solution procedure used for the subproblem. Depending on the size of the example, the subproblem is sometimes difficult or time expensive to be solved as discussed in chapter 4. For this reason, an alternative solution algorithm is suggested by solving a sequence of smaller versions of the subproblem with successive fixing of binary variables before we solve the complete subproblem and get a valid upper bound, Φ^U.

The equipment floor assignment has already been determined by the master problem. The subproblem solution procedure first selects an initial floor; usually the top or the bottom floor. Then, for the chosen floor, an initial set of equipment items is selected and the resulting reduced subproblem [S] is solved for these items *only*. Then, the corresponding non-overlapping binary variables (*i.e.* variables $E1_{ij}, E2_{ij}$

in constraints (4.10) - (4.13)) are fixed to the solution of current subproblem. The next subproblem to be tackled augments the previous set of items by inserting new ones according to user-defined rules. Here, we simply insert new items that are connected to items of the previous iterations and are also allocated to the chosen floor. A maximum number of new inserted items may be imposed in the solution procedure. If none of the remaining items on the floor are connected to the previous ones then we solve the subproblem for all equipment items of the chosen floor.

The resulting subproblem will only involve the non-overlapping binary variables of the new inserted items with respect to existing ones (*i.e.* items considered in all previous iterations) and new items thus reducing significantly the combinatorial nature of the problem. It should also be added that although the non-overlapping binary variables among existing items are fixed, all remaining continuous variables are determined by the optimisation algorithm each time a reduced subproblem is solved.

The above equipment insertion scheme is repeated until all equipment items of the chosen floor are considered. The same procedure is then applied to the neighbouring floor while including all previously examined floors in the same model with all non-overlapping binary variables fixed. The above procedure is repeated until all occupied floors are considered. The last subproblem solved, which involves all plant equipment items, gives a valid upper bound, Φ^U.

The following sets are defined for the description of the iterative algorithm:

Sets

I set of equipment items in the plant

I_k set of equipment items in floor k determined by master problem

Δ set of equipment items considered by subproblem

Θ set of new equipment items inserted

Next, the iterative algorithm used for the solution of the subproblem is outlined:

[*Algorithm U*]

1. Initialise $\Delta = \emptyset$.

2. Select floor, k.

3. Select initial set of equipment items of floor k, Θ and set $\Delta = \Theta$.

4. Solve reduced subproblem $[S]$ for Δ. If $\Delta = I$ STOP.

5. Fix non-overlapping binary variables $E1_{ij}, E2_{ij}$ for $i, j \in \Delta$. If all equipment items of floor k are considered (*i.e.* $\Delta \cap I_k = I_k$) then GOTO Step 7.

6. Insert new equipment items, Θ. Update Δ; $\Delta = \Delta \cup \Theta$. GOTO Step 4.

7. Consider next floor and update k. GOTO Step 6.

Overall, the iterative solution approach uses the same steps as those in Algorithm $[D]$ (described in section 4.1.3) but Step 5 of algorithm $[D]$ is now replaced by algorithm $[U]$ for the subproblem solution to obtain a valid upper bound, Φ^U.

As in the decomposition approach, the optimal solution corresponds to the subproblem solution with the lowest objective function value.

Unlike the decomposition approach, the iterative approach cannot guarantee global optimality due to the iterative insertion scheme used in algorithm [U]. However, as shown later, the solution quality obtained by the iterative approach compares favourably with that of the decomposition approach while reducing significantly the computational requirements.

5.2 Computational Results

In this section, the proposed iterative approach is applied to five examples of process plant layout optimisation. The first four examples are the ones studied in chapter 4 while the fifth one is a larger example with 16 equipment items. The GAMS modelling system was used, coupled with the ILOG CPLEX V6.5 MILP optimisation package. The master problem and the subproblem were solved with 1% margin of optimality on an IBM RS6000. The algorithm terminates when the current lower bound (current master problem solution) and the best upper bound (best subproblem solution) differ less than 5%.

All the data for the first four examples have been presented in chapter 3 (instant coffee plant and ethylene oxide plant, isopropyl alcohol plant) and chapter 4 (maleik anhydride plant) at the respective sections.

5.2.1 Instant Coffee Plant

For the 5-unit instant coffee plant (see Figure 3.3), the decomposition and iterative approaches give identical objective function values for the master and subproblem

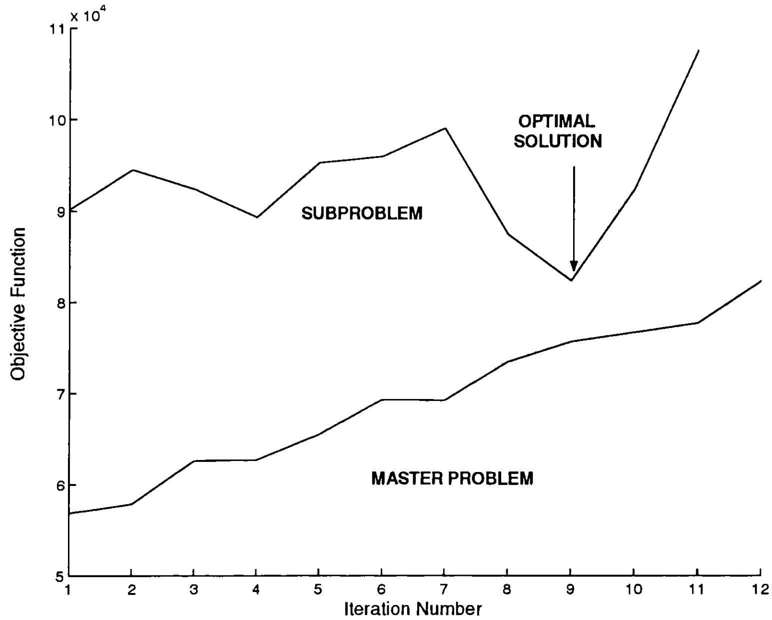

Figure 5.1: Convergence for iterative approach for coffee process

for each iteration as illustrated in Figures 4.1 and 5.1 respectively. The optimal two-floor layout is shown in Figure 5.2. It is worth noting that the optimal layouts for both approaches are equivalent as each of them can easily be derived by shifting appropriately all equipment items along x direction. The optimal equipment orientation and location are given in Table 5.1.

5.2.2 Ethylene Oxide Process

For the ethylene oxide plant(see Figure 3.5), the iterative approach solves the problem in a significantly smaller CPU time than the decomposition and simultaneous approaches (see Table 5.9), thus illustrating the efficiency of the iterative approach. Despite the same value of the objective function as shown in Table 5.8, it is evident from Figures 3.6, 4.3 and 5.3 that there are degenerate solutions. The optimal so-

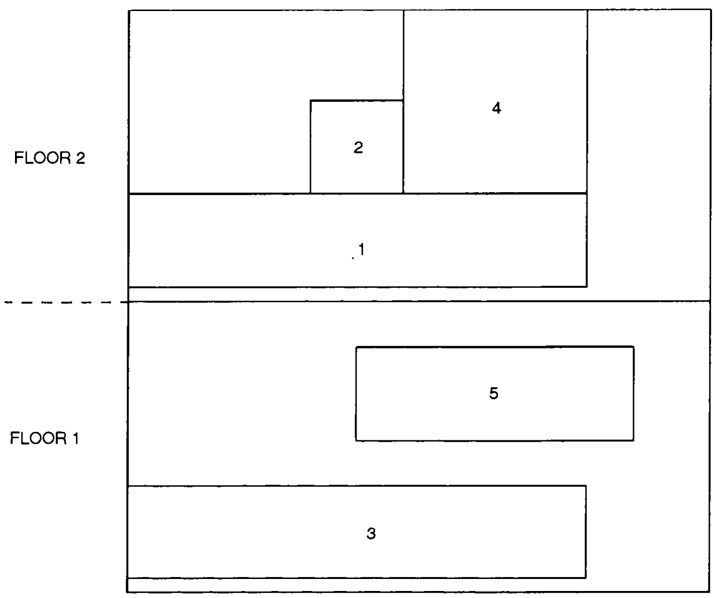

Figure 5.2: Optimal layout for coffee process - Iterative approach

lution is presented in Table 5.2. The algorithm requires 11 iterations as shown in Figure 5.4. It is clear from the same figure that the same subproblem solutions are obtained by both decomposition and iterative approaches apart from the very first iteration.

5.2.3 Cosmetic-Grade Isopropyl Alcohol Plant

For the 12-unit plant manufacturing cosmetic-grade isopropyl alcohol (see Figure 3.9), the iterative approach outperforms again all previous approaches. As shown in Tables 5.8 and 5.9, the approach presented here, solves the problem with a modest CPU time of 413.7 s vs 4457.6 s for the decomposition approach. The optimal solution of the iterative approach (102086 rmu) is also less than 1% higher than the respective one from the decomposition approach. Convergence is achieved in

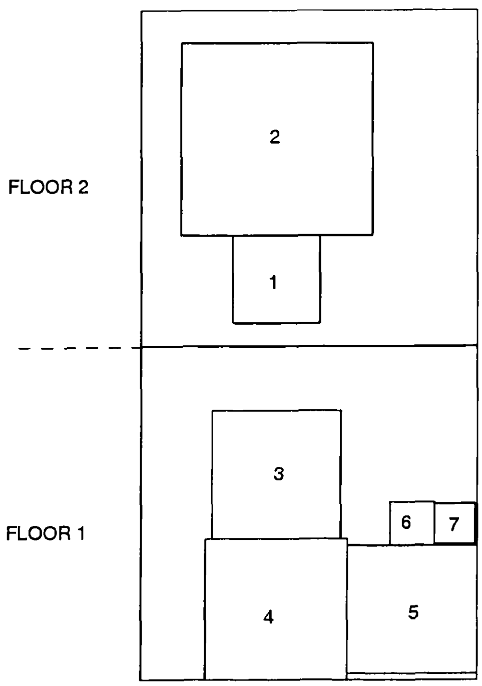

Figure 5.3: Optimal layout for ethylene oxide plant - Iterative approach

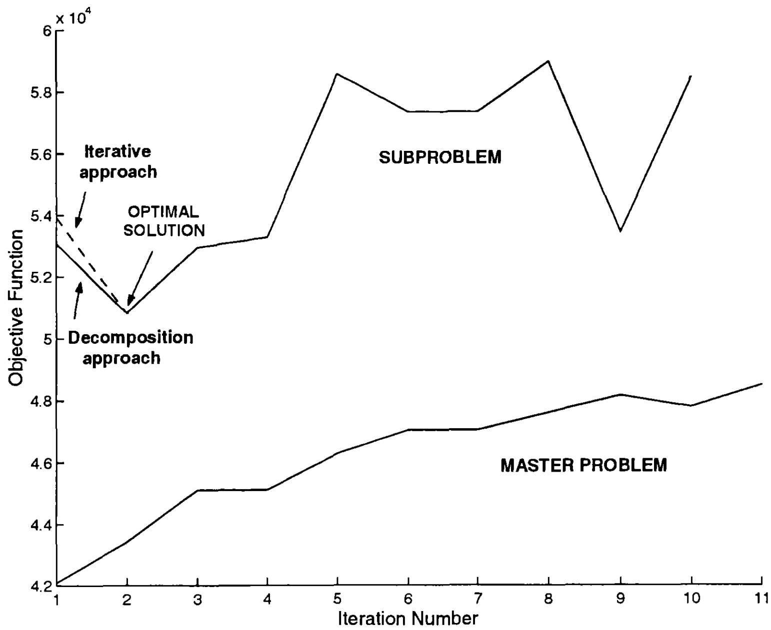

Figure 5.4: Convergence for iterative approach for ethylene oxide process

Table 5.1: Optimal solution for coffee process - Iterative approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	15.8	3.2	7.9	2.1	2
2	3.2	3.2	7.9	5.3	2
3	15.8	3.2	7.9	2.1	1
4	6.3	6.3	12.65	6.85	2
5	9.5	3.2	12.65	6.85	1

93 iterations (see Figure 5.5). The optimal layout details are shown in Figure 5.6 and Table 5.3. The two optimal structures (see Figures 4.6 and 5.6) differ only in the floor allocation of item 11; first floor for the decomposition approach and second floor for the iterative approach. Again, the optimal solution comprises three constructive floors out of four potential ones and the optimal area is 200 m^2.

5.2.4 Maleik Anhydride Plant

As already mentioned in section 4.2.4, the simultaneous and decomposition approaches cannot solve this example within the time limit of 10000 s (see Tables 5.8 and 5.9). On the other hand, the iterative approach solves the problem within 17 iterations while the third iteration obtains the optimal solution (42147 rmu) as shown in Figure 5.7. The optimal layout is presented in Figure 5.8 and Table 5.4. The optimal land area is 100 m^2 ($X^{max} = 10\ m$, $Y^{max} = 10\ m$). Two floors out of

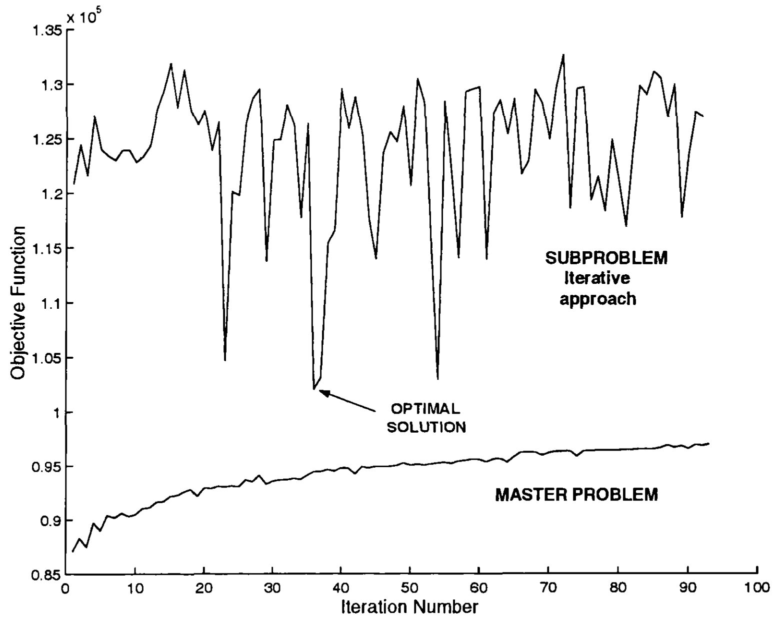

Figure 5.5: Convergence for iterative approach for isopropyl alcohol plant

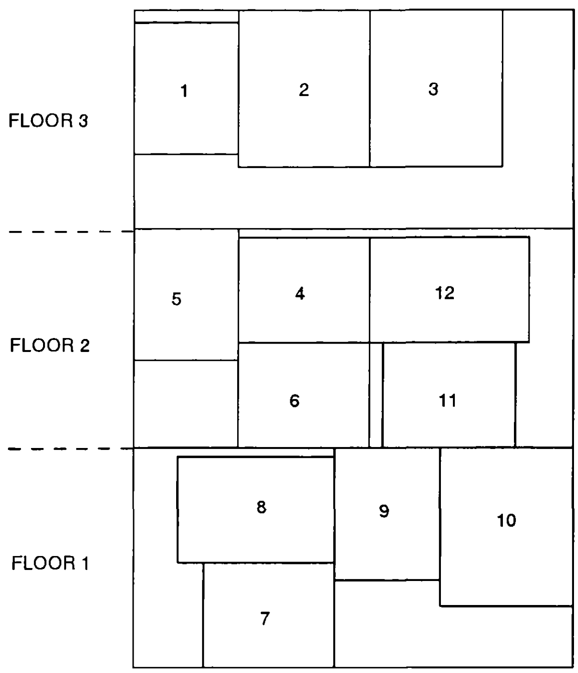

Figure 5.6: Optimal layout for isopropyl alcohol plant - Iterative approach

Table 5.2: Optimal solution for ethylene oxide plant - Iterative approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	5.22	5.22	8.08	4.00	2
2	11.42	11.42	8.08	12.32	2
3	7.68	7.68	8.08	12.32	1
4	8.48	8.48	8.08	4.24	1
5	7.68	7.68	16.16	4.24	1
6	2.60	2.60	16.16	9.38	1
7	2.40	2.40	18.66	9.38	1

the three initially available are finally occupied.

5.2.5 Cis-polybutadiene Plant

Finally, we consider the layout design for a 16-unit cis-polybutadiene plant (Meyers, 1986). The simplified flowsheet is shown in Figure 5.9, while the equipment dimensions and connection and pumping cost data are given in Tables 5.5 and 5.6. The floor construction cost parameters, $FC1$ and $FC2$, are 3330 rmu and 6.6 rmu/m^2, respectively, and the land cost parameter, LC, is 66.7 rmu/m^2.

As shown in Table 5.9, only the iterative approach tackles this example within the time limit of 10000 s while the corresponding optimal solution is presented in Figure 5.10 and Table 5.7. The optimal land area is 100. The simultaneous approach

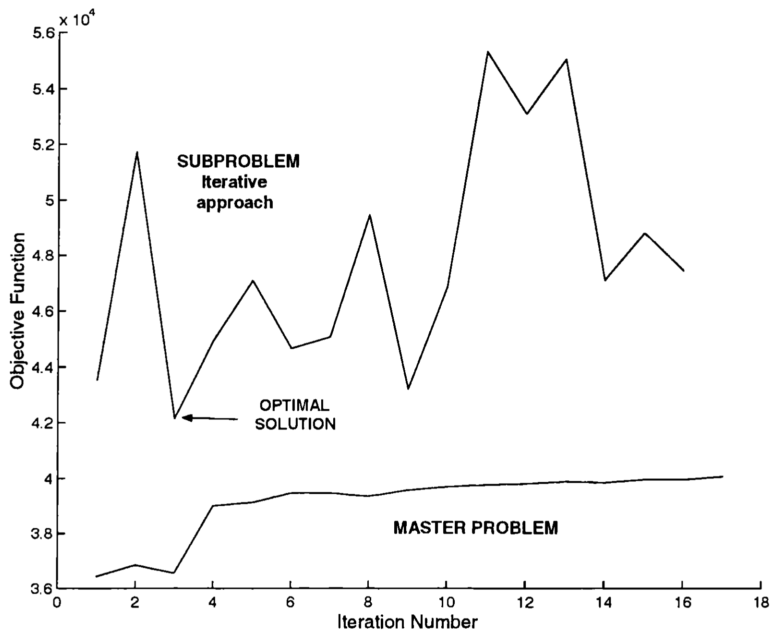

Figure 5.7: Convergence for maleik anhydride example - Iterative approach

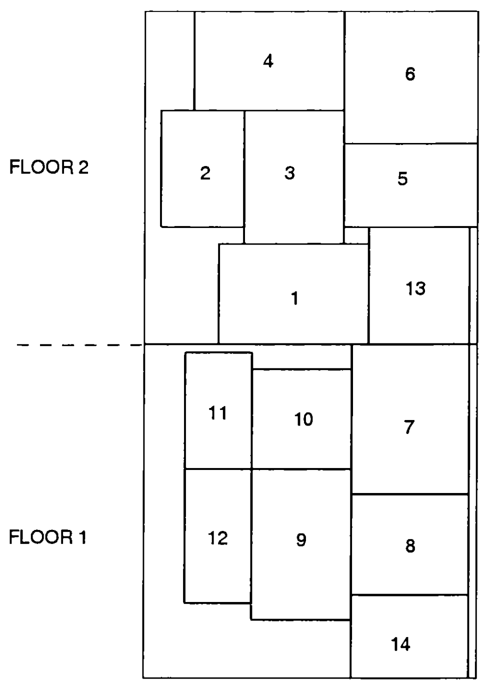

Figure 5.8: Optimal layout for maleik anhydride example - Iterative approach

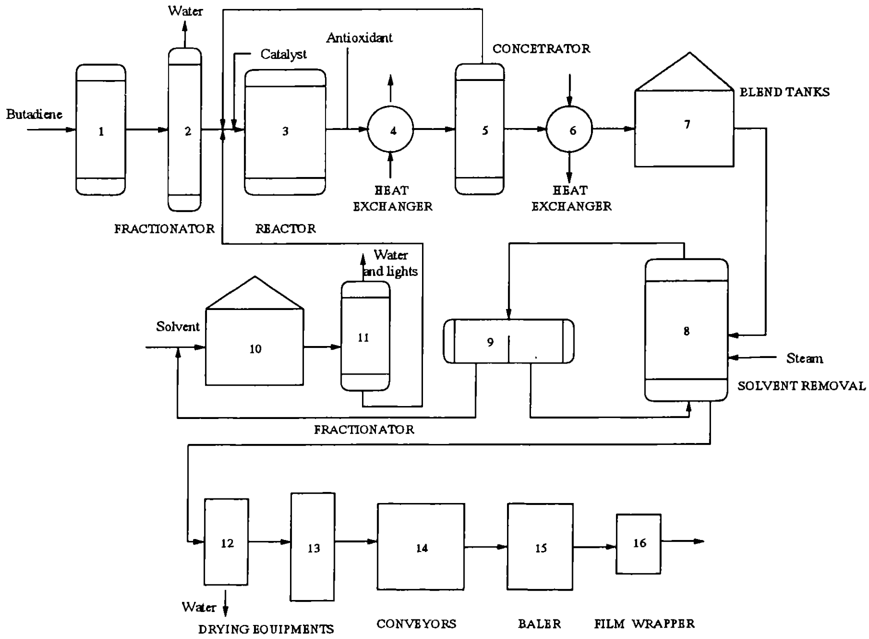

Figure 5.9: Flowsheet for cis-polybutadiene plant

results in an objective function value of 88767 *rmu* (gap of 81.62%) in 10000 *s*. The decomposition approach cannot provide a solution for the subproblem of the first iteration with 1% margin of optimality (objective function value: 51239 *rmu* with a gap of 30.3%). For the iterative approach, a optimal solution of 40602 *rmu* requires 20.7 *s* thus clearly illustrating the enhanced efficiency of this approach. The convergence between solutions of master problem and subproblem is shown in Figure 5.11.

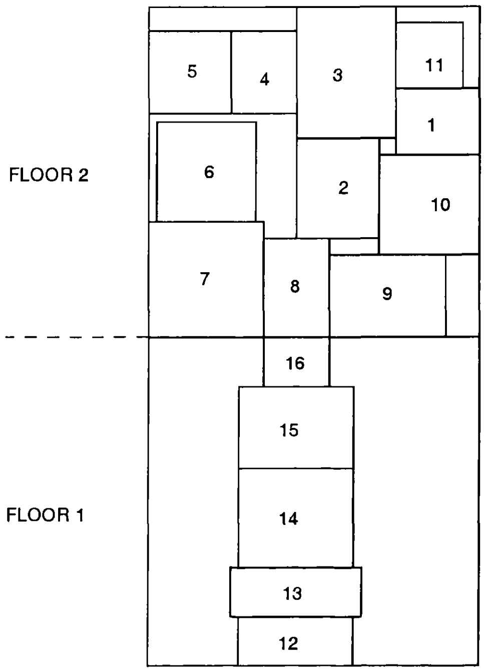

Figure 5.10: Optimal layout for cis-polybutadiene plant - Iterative approach

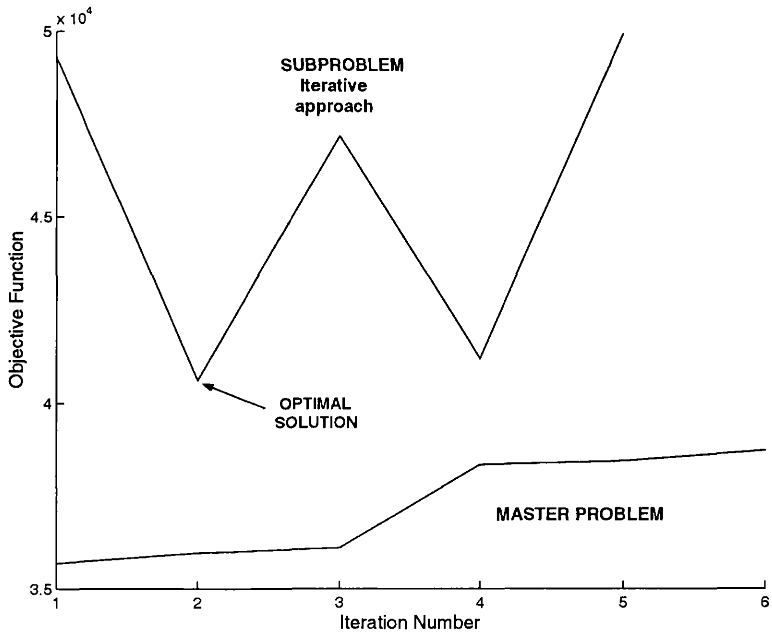

Figure 5.11: Convergence for cis-polybutadiene plant - Iterative approach

5.3 Concluding Remarks

In this chapter, one efficient solution approach for the optimal multi-floor process plant layout problem have been considered based on an iterative solution approach. The proposed approach have been shown to compare favourably with the simultaneous and decomposition approaches (see Tables 5.8 and 5.9) as it proved particularly successful for tackling larger flowsheets (up to 16 units) with modest computational requirements.

Similarly to the previous approaches, the iterative approach determines the number of floors, land area, optimal equipment-floor allocation and equipment location (*i.e.* coordinates and orientation) so as to minimise the total plant layout cost. The applicability of the proposed approach has been demonstrated by five illustrative examples.

As it is evident from section 5.1, algorithm [U] of the iterative approach is based on two user-defined parameters; selection of initial floor (Step 2) and equipment insertion strategy (Step 6). It has been found that better computational performance has been achieved by starting by the top floor for all examples except example 5. Also, it is worth mentioning that the optimal solution was obtained in just a few iterations (usually less than 10 iterations) for most of the examples presented, which can be adopted for larger and/or more complicating flowsheets.

Table 5.3: Optimal solution for isopropyl alcohol plant - Iterative approach

	Orientation		Location		Allocation
Equipment	l_i [m]	d_i [m]	x_i [m]	y_i [m]	Floor
1	4.8	6.0	2.4	6.4	3
2	6.0	7.2	7.8	6.4	3
3	6.0	7.2	13.8	6.4	3
4	6.0	4.8	7.8	7.2	2
5	4.8	6.0	2.4	7.0	2
6	6.0	4.8	7.8	2.4	2
7	6.0	4.8	6.2	2.4	1
8	7.2	4.8	5.6	7.2	1
9	4.8	6.0	11.6	7.0	1
10	6.0	7.2	17.0	6.4	1
11	6.0	4.8	14.4	2.4	2
12	7.2	4.8	14.4	7.2	2

Table 5.4: Optimal solution for maleik anhydride example - Iterative approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	4.50	3.00	4.50	1.50	2
2	2.50	3.50	1.75	5.25	2
3	3.00	4.00	4.50	5.00	2
4	4.50	3.00	3.75	8.50	2
5	4.00	2.50	8.00	4.75	2
6	4.00	4.00	8.00	8.00	2
7	3.50	4.50	8.00	7.75	1
8	3.50	3.0	8.00	4.00	1
9	3.00	4.50	4.75	4.00	1
10	3.00	3.00	4.75	7.75	1
11	2.00	3.50	2.25	8.00	1
12	2.00	4.00	2.25	4.25	1
13	3.00	3.50	8.25	1.75	2
14	3.50	2.50	8.00	1.25	1

Table 5.5: Dimensions of equipment items for cis-polybutadiene plant

Item	α_i $[m]$	β_i $[m]$
1	2.5	2.0
2	2.5	3.0
3	3.0	4.0
4	2.5	2.0
5	2.5	2.5
6	3.0	3.0
7	3.5	3.5
8	3.0	2.0
9	3.5	2.5
10	3.0	3.0
11	2.0	2.0
12	3.5	1.5
13	4.0	1.5
14	3.5	3.0
15	3.5	2.5
16	2.0	1.5

Table 5.6: Connection and pumping costs for cis-polybutadiene plant

Connection	C_{ij}^{c} $[rmu/m]$	C_{ij}^{h} $[rmu/m]$	C_{ij}^{v} $[rmu/m]$
(1,2)	175	525	5250
(2,3)	160	480	4800
(3,4)	205	615	6150
(4,5)	205	615	6150
(5,3)	15	45	450
(5,6)	190	570	5700
(6,7)	190	570	5700
(7,8)	190	570	5700
(8,9)	45	285	2850
(9,8)	15	45	450
(9,10)	30	90	900
(10,11)	35	105	1050
(11,3)	25	75	750
(8,12)	140	420	4200
(12,13)	140	420	4200
(13,14)	140	420	4200
(14,15)	140	420	4200
(15,16)	140	420	4200

Table 5.7: Optimal solution for cis-polybutadiene plant - Iterative approach

	Orientation		Location		Allocation
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$	Floor
1	2.50	2.00	8.75	6.50	2
2	2.50	3.00	5.75	4.50	2
3	3.00	4.00	6.00	8.00	2
4	2.00	2.50	3.50	8.00	2
5	2.50	2.50	1.25	8.00	2
6	3.00	3.00	1.75	5.00	2
7	3.50	3.50	1.75	1.75	2
8	2.00	3.00	4.50	1.50	2
9	3.50	2.50	7.25	1.25	2
10	3.00	3.00	8.50	4.00	2
11	2.00	2.00	8.50	8.50	2
12	3.50	1.50	4.50	0.75	1
13	4.00	1.50	4.50	2.25	1
14	3.50	3.00	4.50	4.50	1
15	3.50	2.50	4.50	7.25	1
16	2.00	1.50	4.50	9.25	1

Table 5.8: Objective function values in *rmu*

	Approach		
Example	Simultaneous	Decomposition	Iterative
coffee plant	82366	82366	82366
ethylene oxide plant	50817	50817	50817
isopropyl alcohol plant	111074	101100	102086
maleik anhydride plant	102335	53919	42147
cis-polybutadiene plant	88767	51239	40602

Table 5.9: CPU times in *s*

	Approach		
Example	Simultaneous	Decomposition	Iterative
coffee plant	3.1	1.5	1.5
ethylene oxide plan	174.0	37.0	7.0
isopropyl alcohol plant	10000.0*	4457.6	413.7
maleik anhydride plant	10000.0*	10000.0*	110.0
cis-polybutadiene plant	10000.0*	10000.0*	20.7

* Computational limit of 10000 *s* is used

Chapter 6

Process Plant Layout with Safety Aspects

The public awareness of industrial hazards in industry has been recently increased due to a number of accidents in chemical process industries. This has led to a need for an in depth consideration of safety aspects within the process plant layout framework during the design or retrofit of a chemical plant, as such decisions can affect significantly the safety of the plant. Moreover, protection devices can considerably reduce the effect of accidents and the financial risk associated with the source item or the propagation of the accident from the source to the target item and may lead to more compact layouts. In this chapter, two different approaches considering the process plant layout problem with safety aspects are presented.

The first approach is an MINLP model which determines simultaneously the coordinates and orientation of each equipment item and the number and type of equipment protection devices to be installed at each item. In this model, the risk related to accidents propagating from a source to a target item is represented by utilising the equivalent TNT method (Lees, 1980; AIChE/CCPS, 1989) as explained in Penteado and Ciric (1996).

The second approach is an MILP model which combines process plant layout and detailed risk assessment by utilising the Dow Fire and Explosion Index System (1994). Quantitative safety evaluation systems like the Dow Fire and Explosion Hazard System (1994) quantify the expected damage caused by fire or explosion and can therefore be considered in a process plant layout problem.

6.1 An MINLP Approach

6.1.1 Problem Statement

In the formulation presented here, rectangular shapes and 90° rotation of items, rectilinear distances between them and connection through their geometrical centres are assumed in the same manner with the multifloor process plant layout case.

The single-floor process plant layout problem with safety aspects can be stated as follows:

Given:

- A set of N equipment items and their dimensions;
- Connectivity network;

- Minimum safety distances between equipment items;
- A collection of protection devices;
- Cost data (connection, equipment purchase, protection device purchase);
- A list of potential events on each unit; and
- An estimate of the probability of an accident propagating from one unit to the other as suggested in Penteado and Ciric (1996).

Determine:

- The detailed layout (orientation, coordinates); and
- The safety devices to be installed at each unit.

So as to minimise the total plant layout cost.

In this section, an MINLP approach is proposed to determine simultaneously the above issues.

This model aims at extending a previous continuous domain process plant layout model (Papageorgiou and Rotstein, 1998) to include safety aspects as suggested in Penteado and Ciric (1996).

6.1.2 Mathematical Formulation

The indices and parameters associated with the safe process plant layout problem are listed below:

Indices

i, j equipment item

d protection device

Parameters

C_{ij} piping cost between items i and j [$\$/m$]

P_{id} protection device cost [$]

D_{ij}^{min} minimum distance between units i and j [m]

M upper bound for distance [m]

P_i probability of an accident at unit i

R_i^0 financial risk of accidents at item i without any protection device available (individual risk) [$]

RF_{id} risk reduction factor when d is installed at i

α_i, β_i dimensions of item i [m]

Φ_{ij}^1, Φ_{ij}^2, Φ_{ij}^3 propagation risk parameters

The formulation is based on the following key variables:

Binary Variables

$E1_{ij}, E2_{ij}$ non-overlapping binary variables (as used in Papageorgiou and Rotstein, 1998)

O_i 1 if length of item i is equal to α_i (*i.e.* parallel to x axis); 0 otherwise

W_{ij}^x 1 if i is to the right of j; 0 otherwise

W_{ij}^y 1 if i is above j; 0 otherwise

Z_{id} 1 if protection device d is installed on item i; 0 otherwise

Continuous Variables

l_i length of item i $[m]$

d_i depth of item i $[m]$

x_i, y_i coordinates of geometrical centre of item i $[m]$

A_{ij} relative distance in y coordinates between items i and j, if i is above j $[m]$

B_{ij} relative distance in y coordinates between items i and j, if i is below j $[m]$

D_{ij} total rectilinear distance between items i and j $[m]$

L_{ij} relative distance in x coordinates between items i and j, if i is to the left of j $[m]$

R_{ij} relative distance in x coordinates between items i and j, if i is to the right of j $[m]$

RR_{ij}^0 financial risk related to accidents propagating from item j (origin) to unit i (target) without any protection device available [$]

Equipment Orientation Constraints

The length and the depth of equipment item i are determined by the equipment orientation constraints (3.6) - (3.7), as presented in section 3.2.2.

Non-overlapping Constraints

In order to avoid situations where two equipment items i and j allocate the same physical location, non-overlapping constraints (4.10) - (4.13) are included in the model.

Distance Constraints

Distance constraints are used to calculate the absolute distances between two equipment items in the $x-$ and $y-$ plane. Constraints (3.16) and (3.17), now written for $i = 1..N-1, j = i+1..N$ are included in the model, in addition with the following constraints:

$$R_{ij} \leq M \cdot W_{ij}^{x} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{6.1}$$

$$L_{ij} \leq M \cdot (1 - W_{ij}^{x}) \qquad \forall\, i = 1..N-1, j = i+1..N \tag{6.2}$$

$$A_{ij} \leq M \cdot W_{ij}^{y} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{6.3}$$

$$B_{ij} \leq M \cdot (1 - W_{ij}^{y}) \qquad \forall\, i = 1..N-1, j = i+1..N \tag{6.4}$$

Binary variables W_{ij}^x and W_{ij}^y are introduced to determine the $\mid x_i - x_j \mid$ and $\mid y_i - y_j \mid$ values, respectively by forcing one variable for each pair (R_{ij}, L_{ij}) and (A_{ij}, B_{ij}) to zero. For instance, if $x_i - x_j > 0$ then $W_{ij}^x = 1$ is the only feasible value. Consequently, $L_{ij} = 0$ by constraints (6.2) while R_{ij} will be equal to the correct value of $x_i - x_j$ by constraints (3.16). On the other hand, if $x_i - x_j < 0$ then $W_{ij}^x = 0$ thus forcing $R_{ij} = 0$ by constraints (6.1) while L_{ij} will obtain the value of $x_j - x_i$ by constraints (3.16). Similar explanation is for the $\mid y_i - y_j \mid$ values.

The total rectilinear distance, D_{ij}, between items i and j is given by:

$$D_{ij} = R_{ij} + L_{ij} + A_{ij} + B_{ij} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{6.5}$$

$$D_{ji} = D_{ij} \qquad \forall\, i = 1..N-1, j = i+1..N \tag{6.6}$$

Additional Layout Constraints

Intersection with the origin of axis should be avoided by introducing constraints (3.20) - (3.21).

Objective Function

The objective function used is the minimisation of the total process plant layout cost associated with connection, protection devices and financial risk:

$$min \sum_i \sum_{j \neq i | f_{ij}=1} C_{ij} \cdot D_{ij} + \sum_i \sum_d P_{id} \cdot Z_{id}$$

$$+\sum_i R_i^0 \prod_d (1 - RF_{id} \cdot Z_{id}) + \sum_j \sum_{i \neq j} RR_{ij}^0 \prod_d (1 - RF_{jd} \cdot Z_{jd})$$

The piping cost is the first term in the objective function, where C_{ij} is the unit piping cost between units i and j taking into account connection costs and other related operating expenses (*e.g* pumping) and f_{ij} is a zero-one connection matrix. The second term represents the cost of protection devices which are assumed to be installed only at the source of accidents. These devices can diminish the probability or the severity of accidents. P_{id} is the cost of protection device d installed at unit i which is the origin of the accident and Z_{jd} is a new binary variable to be determined (1 if protection device d is installed at unit i; 0 otherwise).

The financial risk is captured by the last two terms of the objective function. Similarly to the work presented in Penteado and Ciric (1996), the annual risk is expressed as a function of severity and probability of the accident and can be compared to the connection and protection devices cost by computing the net present financial risk for a given lifetime of the plant and annual interest rate. In particular, the third term corresponds to the risk reduction, when a protection device d is installed at equipment i, in the case of an accident at i. R_i^0 is the initial risk of accidents at item i without any protection device available and RF_{id} is the risk reduction factor when protection device d is installed at item i. Note that for every protection device placed at unit i, the initial risk is reduced by a factor of $(1 - RF_{id})$. The last term is associated with the propagation of an accident from item j (origin) to unit i (target). RR_{ij}^0 is the financial risk related to accidents propagating from item j to item i *without* any protection device available at unit j:

$$RR_{ij}^{0} = P_j e^{-\Phi_{ij}^{1}(D_{ij}-D_{ij}^{min})}(\Phi_{ij}^{2}(D_{ij} - D_{ij}^{min}) + \Phi_{ij}^{3})$$

where parameters Φ_{ij}^1, Φ_{ij}^2 and Φ_{ij}^3 are determined by applying the equivalent TNT method as described in Penteado and Ciric (1996).

The overall problem is formulated as a non-convex MINLP model with non-linear objective function and linear constraints. Next, the applicability of this model is demonstrated by an illustrative example.

6.1.3 Illustrative Example - Ethylene Oxide Plant

In this section, the proposed MINLP formulation is applied to the ethylene oxide plant (see Figure 3.5) derived from the case study presented in Penteado and Ciric (1996) which considers three possible accidents: an explosion in the reactor (unit 1), in the ethylene oxide absorber (unit 3) and in the carbon dioxide absorber (unit 5). The equipment dimensions have been presented in Table 3.4. The probability of an accident to occur is 0.008 yr^{-1} while the initial risk, R_i^0 associated with the destruction of unit 1, 2 and 3 is \$202000, \$64400 and \$49200, respectively (see, Penteado and Ciric, 1996). The available protection devices for installation at equipment items are shown in Table 6.1. The cost and risk reduction factor for every protection device are shown in Tables 6.2 and 6.3, respectively.

The values for parameters Φ_{ij}^1, Φ_{ij}^3 are presented in Tables 6.4 and 6.5, respectively, while $\Phi_{ij}^2 = \Phi_{ij}^1 \Phi_{ij}^3$. The piping cost is 98.4 $\$/m$.

The above MINLP example was modelled in the GAMS system using the DI-

Table 6.1: Available protection devices

Device	Type
$d-1$	additional cooling water
$d-2$	additional overpressure relief devices
$d-3$	additional fire relief devices
$d-4$	second skin on reactor
$d-5$	explosion protection system on reactor
$d-6$	duplicate control system with interlocking flow on reactor
$d-7$	duplicate control shutdown system on absorption tower

COPT++ system (utilising CONOPT 2.0 and ILOG CPLEX 6.5 solvers). The optimal solution is presented in Figure 6.1 and Table 6.6. As expected, the high risk equipment items (units 1, 3, and 5) are located far enough from each other so as to minimise propagation risk. The total plant layout cost is \$244851 with the following breakdown: 6.8% for connection, 20.4%for protection devices, 71.8% for financial risk from individual units and 1% for propagation financial risk cost. The protection devices selected are $d-1$, $d-3$ and $d-7$ for unit 1 and $d-1$ for both units 3 and 5 which are actually the same as the ones selected by Penteado and Ciric (1996).

Table 6.7 and Figure 6.2 show the optimal solution for the case where no protection devices can be installed with a total plant layout cost of \$334289. In that case, there is no protection devices purchase cost but there is a 79% increase in the final risk

Table 6.2: Protection Device Costs

Device	Unit 1	Unit 3	Unit 5
$d-1$	5000	5000	5000
$d-2$	30000	20000	20000
$d-3$	15000	25000	25000
$d-4$	65000		
$d-5$	20000		
$d-6$		30000	30000
$d-7$	20000		

cost.

6.2 An MILP Approach

In the previous section, an MINLP approach was presented determining simultaneously the optimal layout and the number and type of equipment protection devices and representing propagation risk by utilising the TNT equivalent method.

It would be interesting to investigate an alternative approach where a quantitative safety evaluation system is combined with the process plant layout problem. The approach presented here, is based on the Dow Fire and Explosion Hazard System (1994) to quantify the expected damage caused by fire or explosion. By this way, the dangerous equipment items and materials are identified, the distance and area

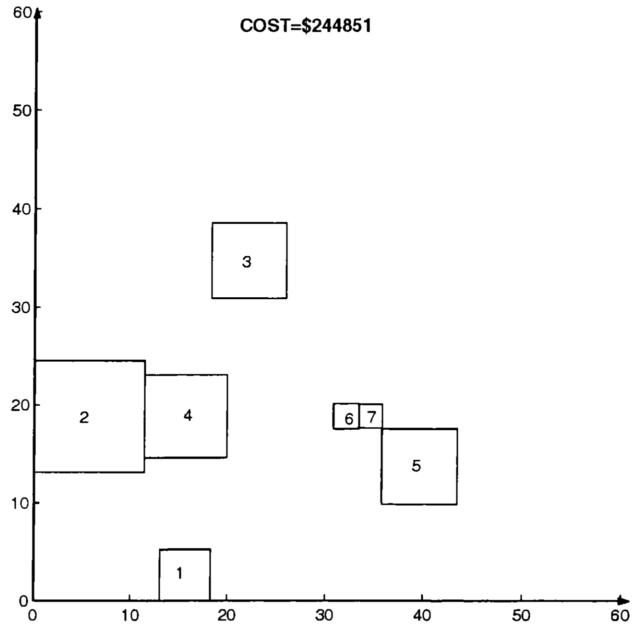

Figure 6.1: Optimal layout

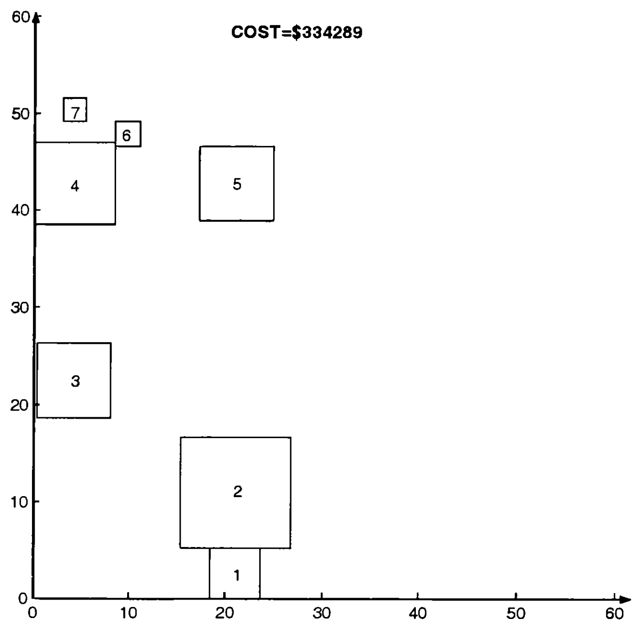

Figure 6.2: Optimal layout - No Protection Devices

Table 6.3: Protection Device Reduction Factor

Device	Unit 1	Unit 3	Unit 5
$d-1$	0.10	0.10	0.10
$d-2$	0.24	0.24	0.24
$d-3$	0.25	0.25	0.25
$d-4$	0.60		
$d-5$	0.20		
$d-6$		0.32	0.32
$d-7$	0.46		

of exposure are calculated, the number and type of protection devices to be installed are selected and the maximum probable property damage and optimal location are determined.

Next, the procedure of the Dow Fire and Explosion Index System (1994) together with an illustrative example based on an ethylene oxide plant is described.

6.2.1 The Dow Fire and Explosion Index System

The Dow Fire and Explosion Index System (1994) is a useful tool to identify the hazardous equipment (*i.e.* equipment that would likely create or escalate an incident) and make engineers aware of the potential losses in each process area. It is based on historic loss data, the energy potential of the processed materials in the chemical plants and the current application of loss prevention practices.

Table 6.4: Parameters Φ^1_{ij}

	Target						
Origin	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7
Unit 1		0.231	0.485	0.205	0.485	0.442	0.489
Unit 3	0.246	0.323		0.345	0.286	0.314	0.223
Unit 5	0.273	0.327	0.225	0.354		0.470	0.279

Table 6.5: Parameters Φ^3_{ij}

	Target						
Origin	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7
Unit 1		82984	807528	30176	613480	37720	2828
Unit 3	16427020	414920		181056	4601084	377200	113160
Unit 5	16427020	539396	6054060	196144		377200	113160

The Fire and Explosion Index, F_i, determines the realistic maximum loss occurred under the most adverse operating conditions and is applicable to processes where flammable, combustible or reactive material is stored or processed.

The procedure includes the following steps:

1. Select the equipment items with the greatest impact on a potential fire or explosion (pertinent process units).

2. Determine the material factor, MF_i, for pertinent process unit i. The material

Table 6.6: Optimal Solution for Example 1

	Orientation		Location	
Equipment	l_i [m]	d_i [m]	x_i [m]	y_i [m]
1	5.22	5.22	2.61	17.31
2	11.42	11.42	19.19	15.69
3	7.68	7.68	29.14	3.84
4	8.48	8.48	29.14	12.72
5	7.68	7.68	42.61	17.31
6	2.60	2.60	37.47	17.31
7	2.40	2.40	47.65	17.31

factor is a measure of the rate of potential energy release from fire or explosion produced by combustion or chemical reaction and is obtained from flammability and instability rankings in the Dow Fire and Explosion Index System (1994).

3. Determine the general process hazards factor, $F1_i$, for pertinent process unit i, which considers hazards applicable to most process situations including exothermic reactions, endothermic processes, material handling and transfer, enclose or indoor process units, access and drainage and spill control.

4. Determine the special process hazard factor, $F2_i$, for pertinent process unit i, which considers specific process conditions that have caused incidents includ-

Table 6.7: Optimal solution for example 1- No Protection Devices

	Orientation		Location	
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$
1	5.22	5.22	21.06	2.61
2	11.42	11.42	21.06	10.93
3	7.68	7.68	4.24	22.47
4	8.48	8.48	4.24	42.74
5	7.68	7.68	21.06	42.74
6	2.60	2.60	9.78	47.88
7	2.40	2.40	4.24	50.38

ing toxic materials, sub-atmosphere pressure, operation in or near flammable range, dust explosion, relief pressure, low temperature, quantity of flammable or unstable material, corrosion and erosion, leakage-joints and packing, use of fired equipment, hot oil heat exchange system and rotating equipment.

5. Calculate the process unit hazard factor, $F3_i$, as follows:

$$F3_i = F1_i \cdot F2_i$$

Typical values of $F3_i$ are within the range of 1-8.

6. Calculate the fire and explosion index, F_i:

$$F_i = F3_i \cdot MF_i$$

In Table 6.8, an indicative list of F_i values and the respective degree of hazard are presented (Dow Fire and Explosion Index System, 1994).

Table 6.8: Fire and explosion index values

F_i Index Range	Degree of Hazard
1-60	Light
61-96	Moderate
97-127	Intermediate
128-158	Heavy
159-up	Severe

7. Calculate the distance of exposure, D_i^e (in m), of item i by:

$$D_i^e = 0.256 \cdot F_i$$

8. Determine the Damage Factor, DF_i, which represents the overall effect of fire plus blast damage resulting from a release of fuel or reactive energy from item i from the values of MF_i and $F3_i$ from literature graphs (Dow Fire and Explosion Index System, 1994).

9. Determine the value of the area of exposure, V_i^e, of pertinent process unit i by calculating the replacement value of the property contained within it (see section 6.2.3).

10. Determine the base maximum probable property damage cost, Ω_i^0 from the product of DF_i and V_i^e (see section 6.2.3).

11. Determine the actual maximum probable property damage cost, Ω_i, as a function of Ω_i^0 and the loss control credit factor γ_{ik} which is introduced when the protection device configuration k is installed on pertinent unit i in order to reduce the probability and the magnitude of a particular incident (see section 6.2.3).

It should be added that the Dow Fire and Explosion Index System (1994) can also estimate the maximum probable days outage thus assessing the potential business interruption from an incident. However, such estimations are not considered in this work.

Next, we apply the above procedure to the ethylene oxide process presented in section 6.1.3. In this process, fresh ethylene, purified air and recycled gas enter a catalytic plug flow reactor which converts ethylene to ethylene oxide, carbon dioxide and water, while a part of ethylene remains unreacted. The hot gases are cooled in a heat exchanger and then enter an ethylene oxide absorption column, where ethylene oxide is stripped out of the gas stream by water. The scrubbed gas is cooled in a heat exchanger and sent to a carbon dioxide absorber. The remaining gases are recycled back to the reactor. The carbon dioxide/water stream is separated in a flash tank and the water is recycled to the carbon dioxide absorber through a recycle pump.

Three possible accidents are considered: an explosion at the reactor, an explosion at the ethylene oxide absorber and an explosion at the carbon dioxide absorber. For this reason, the pertinent process units (Step 1) are the reactor, the ethylene oxide absorber and the carbon dioxide absorber.

According to the Dow Fire and Explosion Index System (1994), the material factor of equipment item i, MF_i, including a mixture is approximated to the highest material factor value of the component with concentration higher than 5%. Thus, the MF_i value (Step 2) is 29 (ethylene oxide value) for both the reactor and the ethylene oxide absorber and 24 (ethylene value) for the carbon dioxide absorber.

The general process hazard (Step 3) and the special process hazard (Step 4) factors are calculated as shown in Table 6.9 and Table 6.10, respectively.

Table 6.9: General process hazards penalties ($F1_i$)

General Process Hazards	Reactor	C_2H_2O Absorber	CO_2 Absorber
Base Factor	1.0	1.0	1.0
Exothermic Reactions	1.0	-	-
Access	0.2	0.2	0.2
$F1_i$	2.2	1.2	1.2

The process units hazard factor (Step 5), the fire and explosion index (Step 6), the distance of exposure (Step 7) and the damage factor (Step 8) for the three pertinent process units are presented in Table 6.11. The last three steps of the procedure (Steps 9-11) will be clarified later in section 6.2.3.

6.2.2 Problem Statement

Overall, the plant layout problem with safety aspects based on Dow Fire and Explosion Index System (1994) can now be restated as follows:

Table 6.10: Special process hazards penalties ($F2_i$)

General Process Hazards	Reactor	C_2H_2O Absorber	CO_2 Absorber
Base Factor	1.0	1.0	1.0
Toxic Material	0.8	0.8	0.8
Purge Failure	0.3	0.3	0.3
Flammable Material	0.15	0.15	0.15
Corrosion/Erosion	0.1	0.1	0.1
Leakage	0.1	0.1	0.1
$F2_i$	2.45	2.45	2.45

Given:

- A set of equipment items and their dimensions;
- Connectivity network;
- A list of potential events on each unit;

Table 6.11: Fire and explosion risk analysis system factors

Equipment Item	MF_i	$F1_i$	$F2_i$	$F3_i$	F_i	D_i^e $[m]$	DF_i
Reactor	29	2.2	2.45	5.39	156.31	40	0.87
C_2H_2O Absorber	29	1.2	2.45	2.94	85.26	21.8	0.73
CO_2 Absorber	24	1.2	2.45	2.94	70.56	18.06	0.66

- A number of potential protection device configurations to be installed on each item and the corresponding loss control credit factors;
- Exposure Distance and Damage factors of items; and
- Cost data (connection, equipment purchase, protection device purchase).

Determine:

- The detailed layout (orientation, coordinates); and
- The safety devices to be installed at each unit.

So as to minimise the total plant layout cost.

The same assumptions as those described in section 6.1.1 are used.

6.2.3 Mathematical Formulation

The indices, parameters and variables associated with the layout problem with safety aspects have been listed in section 6.1.2. The following additional notation is also required.

Indices

I_p set of pertinent items

k protection device configuration

K_i set of protection device configurations suitable for installation on item i

Parameters

C_i^p purchase cost of item i [\$]

D_i^e distance of exposure of item i $[m]$

DF_i damage factor of item i

$F1_i$ general process hazards factor of item i

$F2_i$ special process hazards factor of item i

$F3_i$ process unit hazards factor of item i

F_i fire and explosion index of item i

MF_i material factor of item i

P_{ik} purchase and installation cost of protection device configuration k for item i [\$]

U upper bound for actual maximum probable property damage cost [\$]

γ_{ik} loss control credit factor of protection device configuration k for item i

Binary Variables

Z_{ik} 1 if protection device configuration k is installed on item i; 0 otherwise

Ψ_{ij} 1 if item j is allocated within the area of exposure of item i; 0 otherwise

Continuous Variables

D_{ij}^{in} total rectilinear distance between items i and j if D_{ij} is smaller than D_i^e $[m]$

D_{ij}^{out} total rectilinear distance between items i and j if D_{ij} is larger than D_i^e $[m]$

V_i^e value of area of exposure of item i [\$]

Ω_i^0 base maximum probable property damage cost for pertinent item i [\$]

Ω_i actual maximum probable property damage cost for pertinent item i [\$]

$\overline{\Omega Z}_{ik}$ linearisation variable denoting the product between Ω_i and Z_{ik} [\$]

The mathematical programming formulation presented in this section minimises a cost-based objective function subject to equipment orientation, non-overlapping, distance, base and actual maximum probable damage cost constraints. These constraints are described in detail next.

Equipment Orientation, Non-overlapping and Distance Constraints

Again, constraints (3.6), (3.7), are included in the model to determine equipment orientation decisions. Non-overlapping constraints (4.10) - (4.13), lower bound constraints (3.20) - (3.21) and distance constraints (3.16) - (3.17) and (6.1) - (6.6) are also part of the model.

Area of Exposure Constraints

A process unit j is assumed to be included in the area of exposure of pertinent process unit i if the total rectilinear distance between i and j is less or equal to the exposure distance of i, D_i^e, as calculated by Step 7 (see section 6.2.1). To calculate the value of the area of exposure (Step 9), we need to introduce new variables,

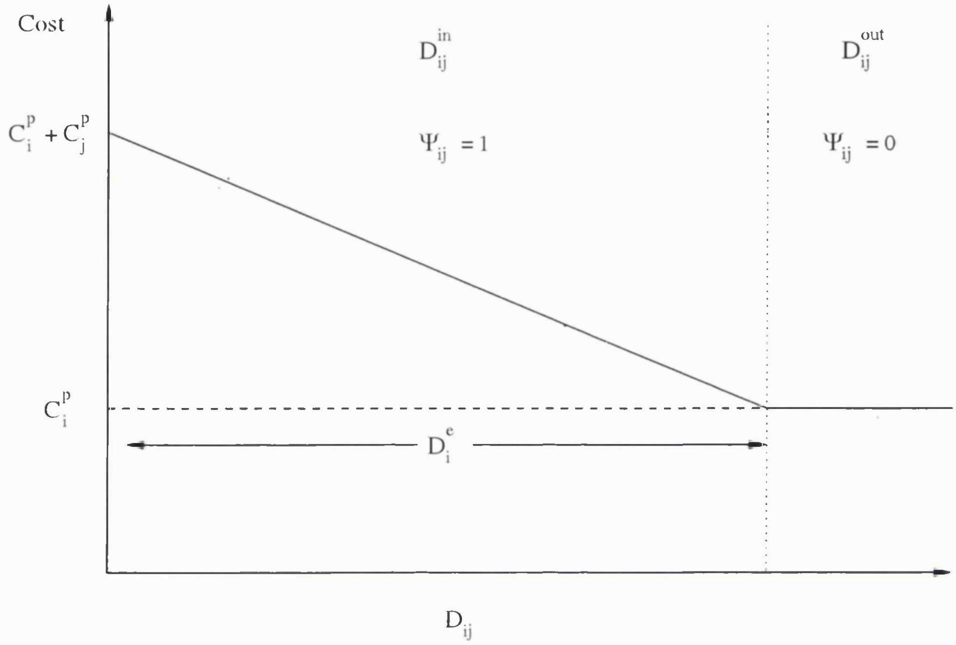

Figure 6.3: Damage cost between source item i and target item j

D_{ij}^{in}/D_{ij}^{out} expressing the distance between i and j, if j is allocated inside/outside the area of exposure of i as illustrated in Figure 6.3. The total rectilinear distance will be equal to the summation of D_{ij}^{in} and D_{ij}^{out}:

$$D_{ij} = D_{ij}^{in} + D_{ij}^{out} \qquad \forall\, i \in I^p, j : i \neq j \tag{6.7}$$

where I^p is the set of pertinent process units. To ensure that only one of D_{ij}^{in} and D_{ij}^{out} will be non-zero, we introduce new binary variables, Ψ_{ij}, together with the following constraints:

$$D_{ij}^{in} \leq D_i^e \cdot \Psi_{ij} \qquad \forall\, i \in I^p, j : i \neq j \tag{6.8}$$

$$D_{ij}^{out} \geq D_i^e \cdot (1 - \Psi_{ij}) \qquad \forall\, i \in I^p, j : i \neq j \tag{6.9}$$

$$D_{ij}^{out} \leq M \cdot (1 - \Psi_{ij}) \qquad \forall\, i \in I^p, j : i \neq j \tag{6.10}$$

If item j is allocated within the exposure area of item i (*i.e.* $D_{ij}^{in} \leq D_i^e$ and $D_{ij}^{out} = 0$) then $\Psi_{ij} = 1$ by constraints (6.8) and (6.10). On the other hand, if item j is outside the area of exposure of item i, $\Psi_{ij} = 0$ is the only feasible solution thus forcing $D_{ij}^{in} = 0$ by constraints (6.8) and $D_{ij}^{out} \geq D_i^e$ by constraints (6.9) while constraints (6.10) are inactive.

Assuming a piecewise linear approximation, see for example Floudas (1990), of the damage cost of source item i and target item j as a function of their total rectilinear distance (see Figure 6.3), the following equation can then describe the value of the area of exposure of item i, V_i^e:

$$V_i^e = C_i^p + \sum_{j \neq i} (C_j^p \cdot \Psi_{ij} - \frac{C_j^p}{D_i^e} D_{ij}^{in}) \qquad \forall\, i \in I^p \tag{6.11}$$

If item j is located in the area of exposure of i (*i.e.* $D_{ij}^{in} \leq D_i^e$ and $\Psi_{ij} = 1$) then the corresponding part of the second term of equation (6.11) will take a non-zero value. If item j is located outside the area of exposure of item i (*i.e.* $D_{ij}^{in} = 0$ and $\Psi_{ij} = 0$) then the contribution of item j in the second term of equation (6.11) will be zero. In the next section, the relation of each term of equation (6.11) to the losses from an accident in the respective unit and the propagation of the accident to the surrounding units is explained in detail.

Maximum Probable Property Damage Constraints

According to Step 10 of the procedure described in section 6.2.1, the base maximum probable property damage cost for a pertinent process unit i, Ω_i^0, is the product of the damage factor, DF_i, and the value of area of exposure of i, V_i^e.

$$\Omega_i^0 = DF_i \cdot V_i^e \qquad \forall\, i \in I^p \tag{6.12}$$

The product of the damage factor with the first term of the exposure area as defined in equation (6.11), represents the expected financial losses of an accident on the source unit i (individual risk). The product of the damage factor with the second term of (6.11) represents the financial losses related with the propagation of the accident from item i to the surrounding items (propagation risk). The installation of a number of protection devices (protection device configuration) on a pertinent process units can reduce the probability and the magnitude of a particular incident on the unit. Each configuration is characterised by a loss control credit factor, γ_{ik}, expressing the reduction on the base maximum probable property damage cost. Thus, the actual maximum probable property damage cost (Step 11) is given by:

$$\Omega_i = \sum_{k \in K_i} \gamma_{ik} \cdot \Omega_i^0 \cdot Z_{ik} \qquad \forall\, i \in I^p \tag{6.13}$$

where K_i is the set of protection device configurations suitable for installation on item i and Z_{ik} a binary variable determining whether protection device configuration k is installed on item i.

One configuration can be installed per pertinent process unit:

$$\sum_{k \in K_i} Z_{ik} = 1 \qquad \forall\, i \in I^p \tag{6.14}$$

Note that the "empty" protection device configuration (*i.e.* no protection device) can also be included as one alternative with loss control credit factor, γ_{ik}, equal to one.

Objective Function

The objective function to be minimised includes the piping cost, the actual maximum probable property damage cost and the cost of protection devices:

$$min \sum_i \sum_{j \neq i} C_{ij} \cdot D_{ij} + \sum_i \Omega_i + \sum_i \sum_{k \in K_i} P_{ik} \cdot Z_{ik}$$

where C_{ij} is the piping cost between items i and j, P_{ik} is the purchase and installation cost of protection device configuration k of item i. The above problem corresponds to an MINLP model which minimises the above objective function subject to constraints (3.6) - (3.7), (4.10) - (4.13), (3.16) - (3.17), (3.20) - (3.21), (4.10) - (4.13) and (6.1) - (6.14). However, the nonlinearities appearing in equation (6.13) in the bilinear product of Ω_i^0 with Z_{ik} can easily be overcome by introducing new continuous variable, $\overline{\Omega Z}_{ik}$, defined as:

$$\overline{\Omega Z}_{ik} \equiv \Omega_i^0 \cdot Z_{ik}$$

which can be determined by the following constraints:

$$\overline{\Omega Z}_{ik} \leq U \cdot Z_{ik} \qquad \forall\, i \in I^p, k \in K_i \tag{6.15}$$

$$\Omega_i^0 = \sum_{k \in K_i} \overline{\Omega Z}_{ik} \qquad \forall\, i \in I^p \tag{6.16}$$

where U is an appropriate upper bound for Ω_i^0. Constraints (6.13) are now written:

$$\Omega_i = \sum_{k \in K_i} \gamma_{ik} \cdot \overline{\Omega Z}_{ik} \qquad \forall\, i \in I^p \tag{6.17}$$

Finally, the resulting problem corresponds to an MILP model which minimises the above objective function subject to constraints (3.6) - (3.7), (4.10) - (4.13), (3.16) - (3.17), (3.20) - (3.21), (4.10) - (4.13) and (6.1) - (6.12), (6.14) - (6.17).

6.2.4 Illustrative Example Revisited

Consider now the example presented in section 6.1.3. The equipment purchase costs are given in Table 6.12. As explained in section 6.2.1, the pertinent process units are the reactor, the ethylene oxide absorber and the carbon dioxide absorber. The available protection devices for installation at equipment items, which are presented in Table 6.1, are the same as those proposed by Penteado and Ciric (1996). A number of safety device configurations are suggested selecting some of the above protection devices and combining their effect to reduce the risk on each one of the pertinent process units. The selected devices, the cost and loss control credit factor for each protection device configuration are shown in Table 6.13 for the reactor and Table 6.14 for the two absorbers.

As before, the example was modelled using the GAMS modelling system coupled with the ILOG CPLEX V6.5 MILP optimisation package. All computational experiments were performed on an IBM RS6000 with 0.1% margin of optimality.

Table 6.12: Equipment dimensions and purchase cost

Equipment	Purchase Cost
Reactor	335000
Heat Exchanger	11000
C_2H_2O Absorber	107000
Heat Exchanger	4000
CO_2 Absorber	81300
Flash Tank	5000
Pump	1500

The optimal layout is shown in Figure 6.4 with a total cost of $290679. The optimal solution (equipment orientation and location) is presented in Table 6.15. As expected pertinent process units are located outside each others area of exposure in order to avoid large Ω_i and propagation of an accident from one unit to the other. The protection device configuration selected for the reactor, the ethylene oxide absorber and the carbon dioxide absorber are $k-5$, $k-2$ and $k-2$, respectively. The purchase cost of protection devices represents 24.1% of the total cost, the financial risk cost 70.6% and the piping cost 5.3%.

Comparing our solution with the one of Penteado and Ciric (1996) where a different allocation of units is chosen (see Figure 6.5) and a different optimal protection device configuration has been selected ($k-4$ for reactor and $k-2$ for absorbers). Using

Table 6.13: Protection device data for the reactor

Configuration	Devices	γ_{ik}	Cost
$k-1$	-	1	0
$k-2$	$d-1$	0.900	5000
$k-3$	$d-3$	0.750	15000
$k-4$	$d-1$, $d-3$, $d-6$	0.365	40000
$k-5$	$d-1$, $d-3$, $d-5$, $d-6$	0.292	60000
$k-6$	$d-1$, $d-3$, $d-4$, $d-5$, $d-6$	0.117	125000

the same configuration as that of Penteado and Ciric (1996), the total plant layout cost is increased to $292345. If we also enforce the relative equipment positioning and the same device configuration as that of Penteado and Ciric (1996) the total plant layout cost is further increased to $292801. Both values are 0.56% and 0.72% higher than our optimal solution.

Finally, we solve the case where there is no investment on protection devices. This can simply be achieved by selecting configuration $k-1$. As expected, the plant layout cost is now increased now to $440848 which is 51.6% higher than the optimal solution. The optimal layout is shown in Figure 6.6 and in Table 6.16. As it can be seen the absence of protection devices force the equipment items to be placed further away than the optimal case (see Figure 6.4).

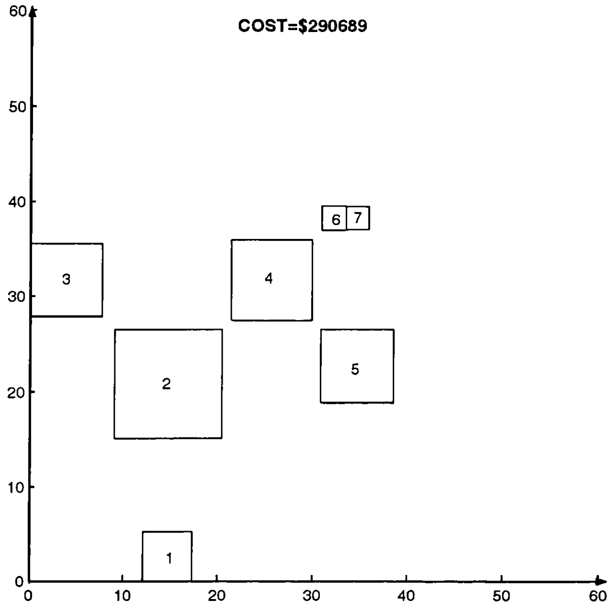

Figure 6.4: Optimal layout

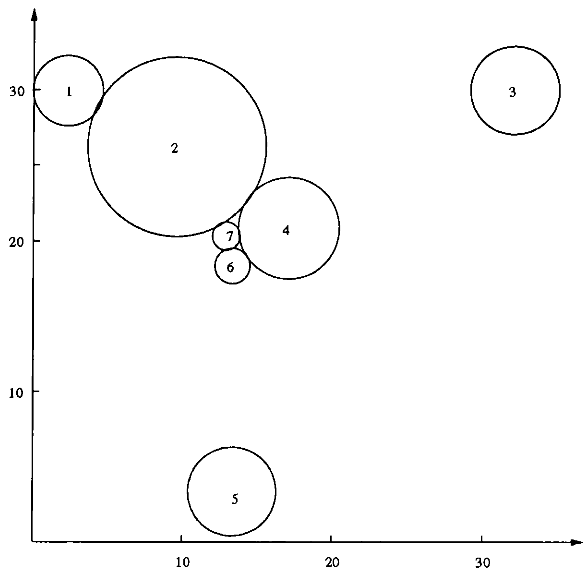

Figure 6.5: Optimal layout (Penteado and Ciric, 1996)

Table 6.14: Protection device data for the ethylene oxide and carbon dioxide absorber

Configuration	Devices	γ_{ik}	Cost
$k-1$	-	1	0
$k-2$	$d-1$	0.900	5000
$k-3$	$d-2$	0.760	20000
$k-4$	$d-1$, $d-2$	0.684	25000
$k-5$	$d-1$, $d-7$	0.612	35000
$k-6$	$d-1$, $d-2$, $d-7$	0.465	55000

6.3 Concluding Remarks

In this chapter, two alternative approaches have been presented which consider the process plant layout with safety aspects.

The first one was a non-convex MINLP model determining simultaneously the process plant layout, the number and type of protection devices and the financial risk associated with accidents and their propagation to neighbouring items. The equivalent TNT method was utilised for the representation of the damage function expressing the effect of the propagation of an accident to an neighbour unit. Because of the non-convexities in the model, global optimal solution cannot be guaranteed.

An alternative MILP approach which combines process plant layout with a detailed risk assessment method by utilising the Dow Fire and Explosion Index System (1994)

Table 6.15: Optimal solution

	Orientation		Location	
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$
1	5.22	5.22	14.74	2.61
2	11.42	11.42	14.74	20.81
3	7.68	7.68	3.84	31.71
4	8.48	8.48	25.64	31.71
5	7.68	7.68	34.67	22.68
6	2.60	2.60	32.17	38.24
7	2.40	2.40	34.67	38.24

has also been presented.

The 7-unit ethylene oxide plant example has been used to demonstrate the applicability of both approaches.

Table 6.16: Optimal solution - No protection devices

	Orientation		Location	
Equipment	l_i $[m]$	d_i $[m]$	x_i $[m]$	y_i $[m]$
1	5.22	5.22	54.36	37.17
2	11.42	11.42	35.44	16.09
3	7.68	7.68	25.89	3.84
4	8.48	8.48	24.94	24.69
5	7.68	7.68	16.86	34.67
6	2.60	2.60	1.30	37.17
7	2.40	2.40	1.30	34.67

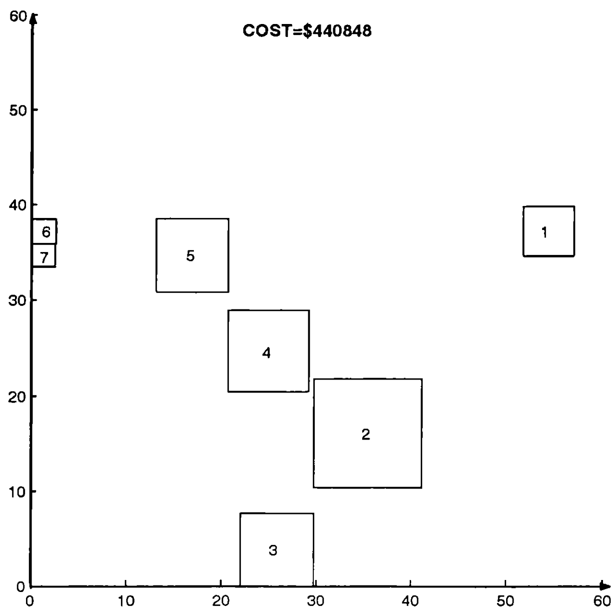

Figure 6.6: Optimal layout - No protection Devices

Chapter 7

Integration of Design, Layout and Production Planning for Pipeless Batch Plants

Pipeless plant is a specific type of batch plants where the transportation of material is taking place through *transferable vessels* from one processing stage to the other. The elimination of pipework offers great flexibility as any material can be transferred in the vessels between two different processing stations, offering quick response to market demands. Plant layout decisions about the allocation of processing stations in the land area determine the vessel transfer times and affect the scheduling of both operation of processing stations and movement of vessels. Realff *et al.* (1996) presented a simultaneous approach considering design, layout and operation. The layout structure was pre-selected and the model decided the position where each station should be allocated adopting a grid-based approach.

There is a need for an approach to determine simultaneously the type of the layout and the allocation of processing stations in the land area of pipeless plant. In this chapter, a unified mathematical framework capturing layout, design, and production planing aspects within the same framework is presented. This work extends the single-floor layout work of Papageorgiou and Rotstein (1998) and the aggregate production model describing the plant operation presented by Realff *et al.* (1996) resulting in a new approach based on a continuous domain represention. Finally, all the common types of pipeless plant layouts (Circular, Herringbone, Linear) along with alternative ones can be selected (see Figure 7.1).

In the next sections, the pipeless plant design, layout and production planning problem is stated and a mathematical programming formulation is presented together with an example.

7.1 Problem Description

The STN representation as defined in Kondili *et al.* (1993) is used for the process recipe of the pipeless batch plant.

States represent type of material or different conditions of transferable vessels considering material held and are denoted by circles. Tasks represent transformation of input states to output states and are denoted by rectangles. Product deliveries and material receipts take place from dedicated storage.

An example of a process recipe is shown in Figure 7.2 (Realff *et al.*, 1996). In

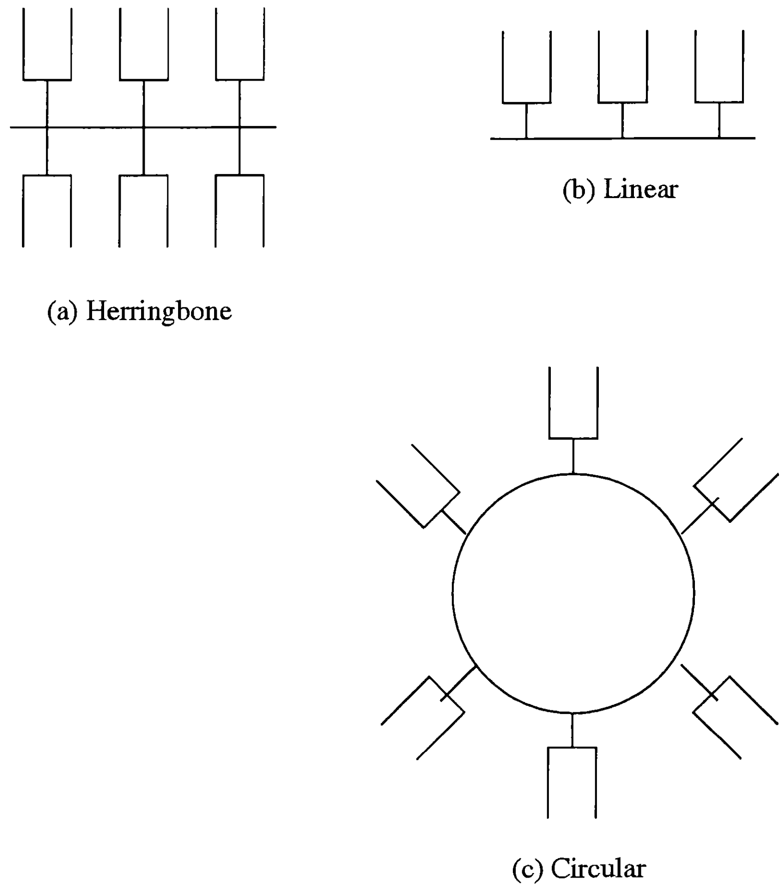

Figure 7.1: Examples of pipeless plants layouts

the first task, the *clean vessels* are being charged with *FeedA* at a charging station. Then, the *charged vessels* are transfered to a reaction station to produce *ReactProd*. After this, there are three options to follow. The first one is to discharge *ProdA* to a storage tank leaving a *clean vessel*. The second one is to blend the vessel content with additive $A1$ at a mixing station, to produce *Prod*1. The third option is similar to the previous one with additive $A2$ to be added for blending to produce *Prod*2. *Prod*1 and *Prod*2 are discharged to storage tanks from the mixing station at the end of the task. In the last task, the *dirty vessels* are cleaned before re-use.

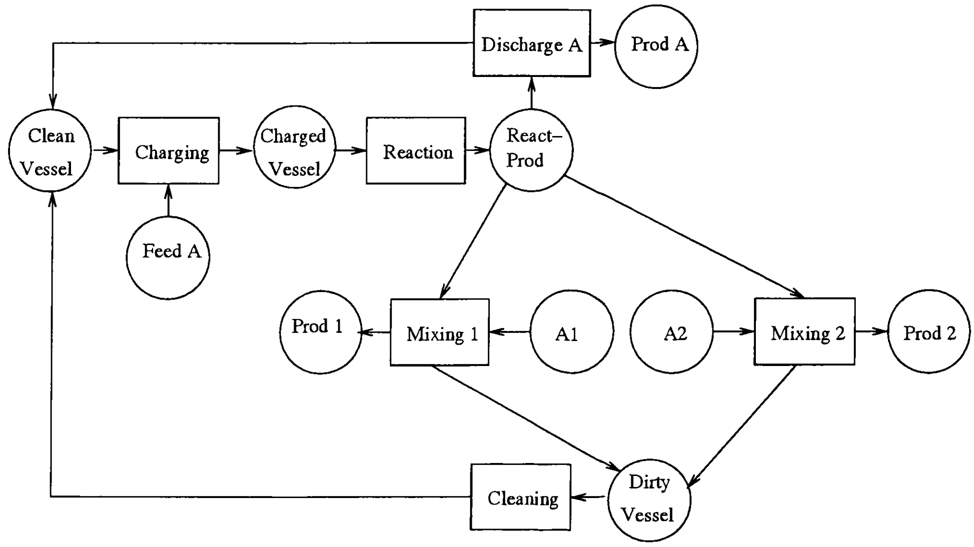

Figure 7.2: Process state-task network

States can represent material discharged in dedicated storage vessels (*Prod*1, *Prod*2, *ProdA*), material feeding processing stations (*FeedA, A1, A2*), different vessel conditions(*Clean vessel, Charged vessel, Dirty vessel*) or intermediate products (*React-Prod*). A number of processing stations should be involved in the plant implementing charging, reaction, mixing and cleaning operations. The plant would also need a number of transferable vessels of different types covering a wide range of specifications including capacities and material properties.

Overall, the problem can be stated as follows:

Given:

- A time horizon;
- A process recipe as STN;
- A set of specialised processing stations. Stations are assumed to require no

cleaning between tasks;

- A set of transferable vessels of different type v with fixed and known batch size. The transferable vessels are assumed to be equipped with their own locomotion mechanism;
- A set of stationary storage vessels dedicated to storage material;
- Product demands and the unit sales price;
- Processing times of tasks at all stations in vessels of type v;
- Capital cost of each station and each type of vessel; and
- Transfer operating cost between stations.

Determine:

- Type and number of processing stations and transferable vessels;
- Detailed layout (i.e. orientation, coordinates) of processing stations; and
- Operating production plan.

So as to maximise a suitable performance criterion (*e.g.* plant profit).

In the formulation presented here, square shapes are assumed for processing stations and rectilinear distances between processing stations are used for a more realistic estimate of the transfer time of the vessels.

A number of vessels carrying material to be processed in a processing station is allowed to wait before the station. In the same manner, a number of vessels carrying material processed in a processing station is allowed to wait after the station. Tasks may have multiple feed or product states. In the first case, *at most* one state can reside in the vessel before the task starts. The others are supplied from dedicated storage vessels. In the second case, *at most* one state remains in the transferring vessel and the rest are deposit in dedicated storage vessels.

7.2 Mathematical Formulation

In this section, the mathematical model for simultaneous design, layout and planning of pipeless plants is presented. It should be added that the proposed model is similar to that of Realff *et al.* (1996) using the same aggregated production planning constraints (see below constraints (7.1) - (7.5)). However, the novelty of the work lies in the layout model which is based in a continuous domain representation rather than a discrete one (Realff *et al.*, 1996).

A number of sets and parameters are associated with the process recipe (STN), plant equipment and process plant layout. These are listed next.

Task i is characterised by:

K_i set of pairs of processing stations j and vessels types v in which task i is performed

H time horizon $[h]$

τ_{ijv} processing time for task i at a station j in a vessel type v, expressed as an integer number of time discretisation intervals

State s is characterised by:

J_s set of processing stations where state s is consumed

$\overline{J}_s$ set of processing stations where state s is produced

T_s set of tasks consuming state s

$\overline{T}_s$ set of tasks producing state s

β_s unit value of material in state s delivered over the time horizon $[rmu/m^3]$

ρ_{is} amount of state s consumed by task i, expressed as a fraction of the nominal vessel capacity

$\overline{\rho}_{is}$ amount of state s produced by task i, expressed as a fraction of the nominal vessel capacity

Processing station j is characterised by:

I_j set of tasks performed at station j

J_j set of candidate stations to be visited by a vessel after station j

C_j capital cost associated with purchase and installation of processing station j $[rmu]$

H_j available time horizon for processing station j $[h]$

N_V total number of processing stations

α_j, β_j dimensions of processing station j $[m]$

Transferable vessel of type v is characterised by:

C_v capital cost associated with purchase of a transferable vessel of type v $[rmu]$

C_v^T transfer cost of vessel of type v between two processing stations $[rmu/m]$

V_v Nominal capacity of vessel of type v $[m^3]$

Process plant layout is characterised by:

θ set of distance sizes

$\overline{D}_\theta$ candidate distance size $[m]$

X^{max}, Y^{max} dimensions of floor area $[m]$

The following key variables are also introduced:

Binary Variables

E_j 1 if station j is included in the design; 0 otherwise

$E1_{jj'}, E2_{jj'}$ non-overlapping binary variables (as used in Papageorgiou and Rotstein, 1998)

O_j 1 if length of station j is equal to α_j (i.e. parallel to x axis); 0 otherwise

$W_{jj'}$ 1 if stations j and j' are included in the design; 0 otherwise

$W_{jj'\theta}$ 1 if candidate distance size $\overline{D}_\theta$ is selected; 0 otherwise

Integer Variables

$M^T_{sj'jv}$ total number of vessels of type v which travel from station j' to station j carrying material s over time horizon

N^0_{sjv} number of vessels of type v, holding state s, waiting to be processed by station j at the beginning of the time horizon

N_{sjv} number of vessels of type v, holding state s, waiting to be processed by station j at the end of the time horizon

$\overline{N}^0_{sjv}$ number of vessels of type v, holding state s, waiting after station j at the start of the time horizon

$\overline{N}_{sjv}$ number of vessels of type v, holding state s, waiting after station j at the end of the time horizon

N^T_v number of transferable vessels of type v to be included in the design

Λ^T_{ijv} total number of batches of task i that takes place in vessels of type v at station j over the time horizon

Continuous Variables

l_j length of station j $[m]$

d_j depth of station j $[m]$

x_j, y_j coordinates of geometrical centre of station j $[m]$

$A_{jj'}$ relative distance in y coordinates between stations j and j', if j is above j' $[m]$

$B_{jj'}$ relative distance in y coordinates between stations j and j', if j is below j' $[m]$

$D_{jj'}$ total rectilinear distance between stations j and j' $[m]$

D_s^e amount of material s delivered to external clients over the time horizon $[m^3]$

$L_{jj'}$ relative distance in x coordinates between stations j and j', if j is to the left of j' $[m]$

$R_{jj'}$ relative distance in x coordinates between stations j and j', if j is to the right of j' $[m]$

R_s^e amount of material s received from external sources over the time horizon $[m^3]$

S_s^0 amount of material s in dedicated storage at the beginning of the time horizon $[m^3]$

S_s amount of material s in dedicated storage at the end of the time horizon $[m^3]$

$\overline{WM}_{sjj'v\theta}$ linearisation variable expressing the product of $W_{jj'\theta}$ and $M^T_{sjj'v}$

$\xi_{jj'}$ 0 if binary variable $W_{jj'}$ is 1, non-zero, otherwise $[m]$

7.2.1 Vessel Balances

The same balance equations are included as presented in Realff *et al.* (1996). The total number of vessels is the summation of the vessels waiting before or after processing at the start of the time horizon, H:

$$N_v^T = \sum_s \sum_j (N_{sjv}^0 + \overline{N}_{sjv}^0) \qquad \forall\, v \tag{7.1}$$

Aggregate balances of the total number of vessels of type v holding material in state s and waiting to be processed in the vicinity of station j over time horizon, H, are also included in the model:

$$N_{sjv} = N_{sjv}^0 + \sum_{j' \in J_j} M_{sj'jv}^T - \sum_{i \in (I_j \cap T_s)} \Lambda_{ijv}^T \qquad \forall\, v, s, j \in J_s \tag{7.2}$$

According to equation (7.2), the number of vessels of type v, carrying material s and waiting for processing at station j at the end of time horizon, H, equals the corresponding number of vessels of type v at the start of the time horizon plus the total number of vessels of the same type which travelled from other stations to station j carrying material s over the entire time horizon minus the total number of batches of all the tasks that took place in a vessel of type v at station j over the time horizon. The respective balances for the vessels waiting at station j after processing are:

$$\overline{N}_{sjv} = \overline{N}_{sjv}^0 - \sum_{j' \in (J_j \cap J_s)} M_{sjj'v}^T + \sum_{i \in (I_j \cap \overline{T}_s)} \Lambda_{ijv}^T \qquad \forall\, v, s, j \in \overline{J}_s \tag{7.3}$$

On a similar manner, equation (7.3) states that the number of vessels of type v, carrying material s and waiting after processing at station j at the end of time horizon, H, equals the corresponding number of vessels of type v at the start of the time horizon minus the total number of vessels of the same type which travelled from station j to the stations carrying material s over the entire time horizon plus the total number of batches of all the tasks that took place in a vessel of type v at station j over the time horizon.

7.2.2 Material Balances

The amount of material held in dedicated storage at the end of time horizon H is equal to the amount in storage at the beginning of the time horizon *plus* the amount produced and the amount received from external sources over the horizon *minus* the amount consumed or delivered to external clients over the time horizon as shown in equation 7.4:

$$S_s = S_s^0 + \sum_{i \in \overline{T}_s} \sum_{(j,v) \in K_i} \overline{\rho}_{is} \cdot V_v \cdot \Lambda_{ijv}^T - \sum_{i \in T_s} \sum_{(j,v) \in K_i} \rho_{is} \cdot V_v \cdot \Lambda_{ijv}^T + R_s^e - D_s^e \qquad \forall\ s \quad (7.4)$$

7.2.3 Station Occupation Constraints

A selected processing station must be occupied less time than the available time horizon:

$$\sum_v \sum_{i \in I_j} \Lambda_{ijv}^T \cdot \tau_{ijv} \leq H_j \cdot E_j \qquad \forall\ j \quad (7.5)$$

If station j is not selected then the corresponding Λ_{ijv}^T variables are forced to zero. It should be noted that H_j can be smaller than than the total time horizon H by appropriate preprocessing depending on process recipe (STN) and initial amount availability.

In order to reduce degenerate solutions for the case of multiple stations of the same type, the following constraints are included:

$$E_{j+1} \leq E_j \tag{7.6}$$

Note that the above constraints allow selection of one station only if the previous one of the same type has been selected.

7.2.4 Station Orientation Constraints

The length and the depth of processing station j are determined by orientation decisions:

$$l_j = \alpha_j \cdot O_j + \beta_j \cdot (E_j - O_j) \qquad \forall\, j \tag{7.7}$$

$$d_j = (\alpha_j + \beta_j) \cdot E_j - l_j \qquad \forall\, j \tag{7.8}$$

$$O_j \leq E_j \qquad \forall\, j \tag{7.9}$$

If station j is not selected (*i.e.* $E_j = 0$) then O_j, l_j and d_j are forced to zero from constraints (7.9), (7.8) and (7.7), respectively. If station j is selected then constraints (7.8) and (7.7) are "transformed" to constraints (3.6) and (3.7).

7.2.5 Non-overlapping Constraints

To avoid situations where two processing j and j' occupy the same physical location the following constraints are going to be included in the model to prohibit overlapping of their stations footprint projections, either in x or y direction:

$$x_j - x_{j'} + M \cdot (1 - W_{jj'} + E1_{jj'} + E2_{jj'}) \geq \frac{l_j + l_{j'}}{2} \qquad \forall\, j = 1..N^V - 1, j' = i + 1..N^V \tag{7.10}$$

$$x_{j'} - x_j + M \cdot (2 - W_{jj'} - E1_{jj'} + E2_{jj'}) \geq \frac{l_j + l_{j'}}{2} \qquad \forall\, j = 1..N^V - 1, j' = i + 1..N^V \tag{7.11}$$

$$y_j - y_{j'} + M \cdot (2 - W_{jj'} + E1_{jj'} - E2_{jj'}) \geq \frac{d_j + d_{j'}}{2} \qquad \forall\, j = 1..N^V - 1, j' = i + 1..N^V \tag{7.12}$$

$$y_{j'} - y_j + M \cdot (3 - W_{jj'} - E1_{jj'} - E2_{jj'}) \geq \frac{d_j + d_{j'}}{2} \qquad \forall\, j = 1..N^V - 1, j' = i + 1..N^V \tag{7.13}$$

where M is an appropriate upper bound. $W_{jj'}$ is a binary variable denoting whether both stations j and j' are included in the design and is defined through the following constraints:

$$W_{jj'} \geq E_j + E_{j'} - 1 \qquad \forall\, j = 1..N^V - 1, j' = i + 1..N^V \tag{7.14}$$

$$W_{jj'} \leq E_j \qquad \forall\, j = 1..N^V - 1, j' = i + 1..N^V \tag{7.15}$$

$$W_{jj'} \leq E_{j'} \qquad \forall\, j = 1..N^V - 1, j' = i + 1..N^V \tag{7.16}$$

Note that the constraints (7.10) - (7.13) are inactive when one of the stations j or j' is not selected in the design (*i.e.* $W_{jj'} = 0$).

7.2.6 Distance Constraints

The relative distances in x- and y- coordinates between stations j and j' is given by the following equations:

$$R_{jj'} - L_{jj'} = x_j - x_{j'} \qquad \forall\, j, j' \in J_j \tag{7.17}$$

$$A_{jj'} - B_{jj'} = y_j - y_{j'} \qquad \forall\, j, j' \in J_j \tag{7.18}$$

Thus, the total rectilinear distance between stations j and j' is:

$$D_{jj'} = R_{jj'} + L_{jj'} + A_{jj'} + B_{jj'} - \xi_{jj'} \qquad \forall\, j, j' \in J_j \tag{7.19}$$

where $\xi_{jj'}$ is a slack variable which takes a zero value when both j and j' are selected (*i.e* $W_{j'j} = 1$):

$$\xi_{jj'} \leq M \cdot (1 - W_{jj'}) \qquad \forall\, j, j' \in J_j, j < j' \tag{7.20}$$

$$\xi_{jj'} \leq M \cdot (1 - W_{j'j}) \qquad \forall\, j, j' \in J_j, j' < j \tag{7.21}$$

In the case where either j or j' or both are not selected $\xi_{jj'}$ is forced to take an non-zero value because the distance between the two stations, $D_{jj'}$, has to be zero in order to maximise the objective function described in section 7.2.8.

7.2.7 Additional Layout Design Constraints

Lower bound constraints on the coordinates of the geometrical centre are included in order to avoid intersection of stations with the origin of axes:

$$x_j \geq \frac{l_j}{2} \qquad \forall\, j \tag{7.22}$$

$$y_j \geq \frac{d_j}{2} \qquad \forall\, j \tag{7.23}$$

A rectangular shape of land area is assumed to be used and its dimensions are determined by:

$$x_j + \frac{l_j}{2} \leq X^{max} \qquad \forall\, j \tag{7.24}$$

$$y_j + \frac{d_j}{2} \leq Y^{max} \qquad \forall\, j \tag{7.25}$$

7.2.8 Vessels Occupation Constraints

To ensure that the occupation of the vessels of type v does not exceed the total available time we introduce the following constraint:

$$\sum_j \sum_{i \in I_j} \Lambda^T_{ijv} \cdot \tau_{ijv} + \sum_s \sum_{j \in \overline{J}_s} \sum_{j' \in (J_j \cap J_s)} D_{jj'} \cdot M^T_{sjj'v} \leq H \cdot N^T_v \qquad \forall\, v \tag{7.26}$$

The first term expresses the vessel occupation time during processing and the second term represents the transfer time between stations[1].

7.2.9 Objective Function

The overall objective function maximises the difference between revenues and operating and capital costs:

$$max \qquad \sum_s \beta_s \cdot D^e_s - \sum_v \sum_s \sum_{j \in \overline{J}_s} \sum_{j' \in (J_j \cap J_s)} C^T_v \cdot D_{jj'} \cdot M^T_{sjj'v} - \lambda \cdot (\sum_j C_j \cdot E_j + \sum_v C_v \cdot N^T_v)$$

where λ is an annualisation cost factor. The first term represents revenues from product deliveries to external clients and the second one the total transfer cost of all the vehicles of all types. The last two terms represent the annualised capital cost associated with the purchase and installation of station j (third term) and the purchase of transferable vessels (fourth term).

The problem maximises the above objective function subject to constraints (7.1) - (7.26). The above problem is an MINLP model because of nonlinearities in the sec-

[1] a vehicle velocity of $1m$/time interval is assumed

ond term of the objective function and the second left hand side term of constraint (7.26). However, the distance between the two processing stations can be approximated as its value can be chosen from a set of candidate distance sizes, $\overline{D}_\theta$. Then, the binary variable $W_{jj'\theta}$ is introduced together with the following constraints:

$$D_{jj'} = \sum_\theta \overline{D}_\theta \cdot W_{jj'\theta} \qquad \forall\, j, j' \in J_j \tag{7.27}$$

where $W_{jj'\theta}$ is 1 if the distance between stations j and j' is equal to $\overline{D}_\theta$. By introducing the above approximation, the second term of the objective function and second left-hand side term of constraints (7.26) now result in bilinear terms which can easily be linearised by introducing new continuous variables, $\overline{WM}_{sjj'v\theta}$:

$$\overline{WM}_{sjj'v\theta} \equiv W_{jj'\theta} \cdot M^T_{sjj'v}$$

defined by:

$$\overline{WM}_{sjj'v\theta} \leq U \cdot W_{jj'\theta} \qquad \forall\, s, v, \theta, j \in \overline{J}_s, j' \in (J_j \cap J_s) \tag{7.28}$$

$$M^T_{sjj'v} = \sum_\theta \overline{WM}_{sjj'v\theta} \qquad \forall\, s, v, \theta, j \in \overline{J}_s, j' \in (J_j \cap J_s) \tag{7.29}$$

where U is a valid upper bound for $M^T_{sjj'v}$. $W_{jj'\theta}$ will take only one non-zero value if stations j and j' are included in the design:

$$\sum_\theta W_{jj'\theta} = W_{jj'} \qquad \forall\, j, j' \in J_j, j < j' \tag{7.30}$$

$$\sum_{\theta} W_{jj'\theta} = W_{j'j} \qquad \forall\, j, j' \in J_j, j' < j \tag{7.31}$$

Constraints (7.26) are now re-written as:

$$\sum_{j}\sum_{i\in I_j} \Lambda^T_{ijv} \cdot \tau_{ijv} + \sum_{s}\sum_{j\in \overline{J}_s}\sum_{j'\in(J_j\cap J_s)}\sum_{\theta} \overline{D}_\theta \overline{WM}_{sjj'v\theta} \leq HN^T_v \qquad \forall\, v \tag{7.32}$$

Finally, the resulting MILP problem can be summarised as follows:

$$max \qquad \sum_{s} \beta_s \cdot D^e_s - \sum_{v}\sum_{s}\sum_{j\in J_s}\sum_{j'\in(J_j\cap J_s)}\sum_{\theta} C^T_v \cdot \overline{D}_\theta \cdot \overline{WM}_{sjj'v\theta} - \lambda \cdot (\sum_{j} C_j \cdot E_j + \sum_{v} C_v \cdot N^T_v)$$

subject to constraints (7.1) - (7.25) and (7.27) -(7.32)

All continuous variables in the formulation are defined as non-negative.

Next, one illustrative example is presented to demonstrate the applicability of the MILP model.

7.3 A Pipeless Batch Plant Example

The process recipe introduced in section 7.2 is considered. The time horizon is discretised into a number of time intervals of equal duration. Considering a daily production ($H = 24h$) the overall horizon will be discretised in 96 $\frac{1}{4}$ 15 *min* intervals. All system events are forced to coincide with the interval boundaries. It is desired to design a plant producing all products *ProdA, Prod1, Prod2* on a daily basis. In Table 7.1 the minimum and maximum daily demands are presented as well as the unit value added, in relative money units (*rmu*), including the cost of the consumed raw material and utilities.

Table 7.1: Product Data

Product	Min. Demand [m^3]	Max. Demand [m^3]	β_s [rmu/m^3]
ProdA	100	130	5.0
Prod1	150	180	5.5
Prod2	150	180	6.0

Twelve processing stations ($1m \times 1m$) of six different station types suitable for the recipe tasks are possible selection in the plant. All station details are shown in Table 7.2. The second and third columns of Table 7.2 list the suitable tasks that each station may perform together with the corresponding processing time. The third column gives the maximum number of each station type allowed in the plant. The last column provides the daily equivalent of the annualised capital cost associated with the purchase and installation of processing stations (Realff *et al.*, 1996).

Each type of station differs from the other on its functionality (i.e. type of tasks that can be carried out in the station) or the processing time of a certain task. For example, *Charger* and *Reactor (A)* are suitable for different tasks - *Charging* and *Reaction* respectively - and *Mixer (A)* and *Mixer (B)* have different processing times for the same task (*i.e. Mixing 1*). Note that *Mixer (A)* carries out the task faster than *Mixer (B)* but it is more expensive. The two mixing stations (*Mixer (A)* and *Mixer (B)*) are already multipurpose in functionality as they can be used for more than one task.

One type of vessels is selected and a maximum number of 15 vessels is allowed.

Table 7.2: Processing Stations Data

Station Type	Suitable Task	Processing Time [h]	Maximum Number	Capital Cost [rmu]
Charger	Charging	$\frac{1}{2}$	2	20
Reactor (A)	Reaction	$\frac{1}{2}$	2	60
Reactor (B)	Reaction	$\frac{3}{4}$	2	40
Mixer (A)	Mixing 1	$\frac{1}{2}$	2	70
	Mixing 2	$\frac{1}{2}$		
	Discharge A	$\frac{1}{2}$		
Mixer (B)	Mixing 1	$\frac{3}{4}$	2	50
	Mixing 2	$\frac{3}{4}$		
	Discharge A	$\frac{1}{2}$		
Cleaner	Cleaning	$\frac{1}{2}$	2	30

The nominal capacity and the purchase cost of each vessel are 10 m^3 and 15 rmu, respectively. Finally, a transfer cost of 0.5 rmu/m is used for the movement of vessels between processing stations.

The GAMS modelling system was used, coupled with the ILOG CPLEX V6.5 MILP optimisation package. The example was solved with 3% margin of optimality on an IBM RS6000.

The optimal layout is presented in Figure 7.3. In total seven processing stations are chosen including 2 Chargers, 2 Reactors of type B, 2 Mixers of type B and one

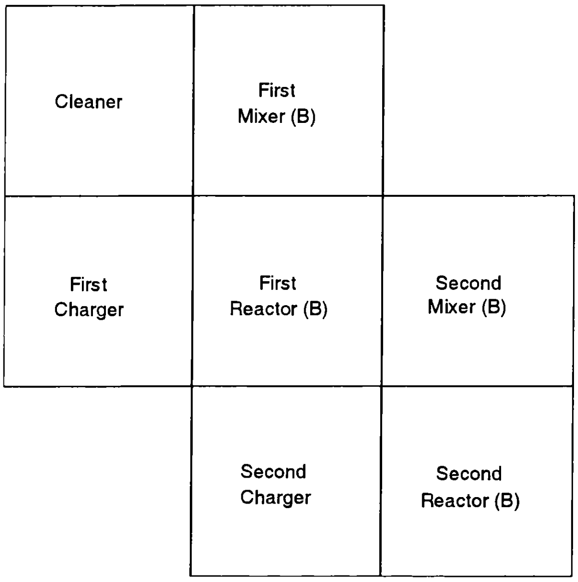

Figure 7.3: Optimal Layout

Cleaner together with 7 transferable vessels. The optimal location of each processing stations is presented in Table 7.3. The maximum demands for all products have been met while the optimal objective function value is 2265.5 *rmu*. Table 7.4 presents the number of batches of each task taking place at each processing station.

Next, we enforce a herringbone ($X^{max} = 2$ or $Y^{max} = 2$) and a linear layout ($X^{max} = 1$ or $Y^{max} = 1$) resulting in the layouts presented in Figure 7.4 and Table 7.5 and Figure 7.5 and Table 7.6, respectively. The optimal objective function value is 2262 *rmu* for the herringbone and 2218 *rmu* for the linear case. The above values differ less than 3% from the optimal objective function.

The model presented here differs from the aggregate discrete model presented in the work of Realff *et al.* (1996) in the allocation of the processing stations in the land area. In the aggregate model, processing stations can be allocated to only 8 pre-

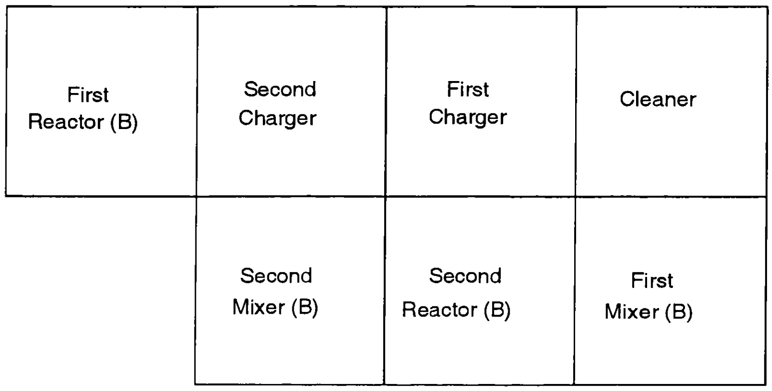

Figure 7.4: Optimal Layout - Herringbone Layout

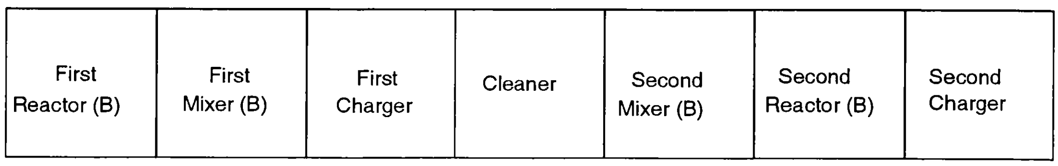

Figure 7.5: Optimal layout - Linear Layout

Table 7.3: Optimal Location

Processing Station	x_i $[m]$	y_i $[m]$
First Charger	0.5	1.5
Second Charger	1.5	0.5
First Reactor (B)	1.5	1.5
Second Reactor (B)	2.5	0.5
First Mixer (B)	1.5	2.5
Second Mixer (B)	2.5	1.5
Cleaner	0.5	2.5

defined positions of a Herringbone layout. In this work, stations can be allocated anywhere in the land area as long as their between distance is equal to one of the candidate distance sizes $\overline{D}_\theta$[2]. An attempt to increase the available positions in the discrete model in order to include all possible locations would increase significantly the size of the model.

7.4 Concluding Remarks

In this chapter, the integration of design, layout and production planning of pipeless plants has been considered. A general mathematical formulation has been described, which determines simultaneously the above issues maximising the difference between

[2] 11 candidate distance sizes between stations have been used

Table 7.4: Number of batches

Task	Processing Station	Batch $[m^3]$
Charging	First Charger	31
Charging	Second Charger	18
Reaction	First Reactor (B)	31
Reaction	Second Reactor (B)	18
Mixing 1	First Mixer (B)	18
Mixing 1	Second Mixer (B)	0
Mixing 2	First Mixer (B)	12
Mixing 2	Second Mixer (B)	6
Discharge A	First Mixer (B)	0
Discharge A	Second Mixer (B)	13
Cleaning	Cleaner	36

revenues from product deliveries to external clients and the total transfer and annualised capital cost. The resulting optimisation problem corresponds to an MILP model which have been applied successfully to a literature example.

The model compares favourably to previous approaches (Realff *et al.* 1996) as it decides upon the type of the layout and provides a more flexible way of allocating stations in the land area.

Table 7.5: Optimal Location - Herringbone Layout

Processing Station	x_i [m]	y_i [m]
First Charger	2.5	1.5
Second Charger	1.5	1.5
First Reactor (B)	0.5	1.5
Second Reactor (B)	2.5	0.5
First Mixer (B)	3.5	0.5
Second Mixer (B)	1.5	0.5
Cleaner	3.5	1.5

Table 7.6: Optimal Location - Linear Layout

Processing Station	x_i [m]	y_i [m]
First Charger	2.5	0.5
Second Charger	6.5	0.5
First Reactor (B)	0.5	0.5
Second Reactor (B)	5.5	0.5
First Mixer (B)	4.5	0.5
Second Mixer (B)	1.5	0.5
Cleaner	3.5	0.5

Chapter 8

Conclusions and Future Directions

This thesis has been considered the development of new quantitative experimental methods based on mathematical programming models to assist engineers in generating optimal process plant layouts. A number of mathematical models and solution procedures have been developed for the process plant layout problem to account for multifloor, safety and pipeless operation. The key contributions of the thesis are summarised in the next section, while section 8.2 considers possible directions for future work.

8.1 Contributions of this thesis

8.1.1 Multifloor Process Plant Layout

The ultimate goal of this stage was the development of efficient solution approaches based on mixed integer optimisation models, in order to determine:

- Number of floors;
- Floor location of each equipment item; and
- Spatial allocation of equipment items that have been assigned to the same floor.

In terms of solution and analysis of the models, three solution approaches have been investigated: a simultaneous, a decomposition and an iterative approach.

Simultaneous Approach

The outcome has been a general mathematical programming formulation for the multi-floor process plant layout problem, which considers a number of cost and management/engineering drivers within the same framework thus resolving various trade-offs at an optimal manner. The proposed model determines simultaneously the number of floors, land area, floor allocation of each equipment item and detailed layout for each floor. The overall problem has been formulated as a mixed integer linear programming (MILP) model based on a continuous domain representation (Papageorgiou and Rotstein, 1998).

The model minimises the total plant layout cost (connection, pumping, land area and floor construction costs) subject to floor constraints (allocate each equipment item to one floor and calculate the number of floors), equipment orientation constraints (determine the length and depth of each item), non-overlapping constraints (avoid situations where two equipment items occupy the same physical location when allocated to the same floor), distance constraints (calculate the absolute distances between equipment items) and additional layout design constraint (calculate the land and floor area).

The resulting mixed integer optimisation problem is solved at a single-level (simultaneous approach) by using standard branch-and-bound procedures. All decisions are considered simultaneously within the same framework and optimality is guaranteed for tractable models. Flowsheets up to 11-units have been solved for the multi-floor process plant layout problem.

Decomposition Approach

Here, the overall problem has been decoupled into a master and a subproblem, which are solved iteratively until convergence. The master problem provides a lower bound to the optimal solution of the original problem. The number of floors and the allocation of units to floors are determined by the master problem. Then, the solution of the subproblem provides an upper bound to the optimal solution of the original problem and determines the detailed layout for every floor. The master problem and the subproblem are solved iteratively until convergence, with an acceptable tolerance. The master problem minimises a relaxation of connection and pumping costs, the floor construction and the land area costs while the subproblem is a reduced simultaneous model. Flowsheets up to 12 items have been tackled for the multi-floor problem with this approach.

Iterative Approach

In the previous approach, the subproblem is sometimes difficult to be solved, depending on the size of the example. In order to overcome this difficulty, an alternative new approach has been suggested where the same models as above are used for the master problem and the subproblem. An iterative solution algorithm has been followed though for the subproblem by solving a sequence of smaller versions of the subproblem with the corresponding non-overlapping binary variables fixed to the solution of current subproblem. The iterative approach compares favourably to the two previous approaches considering the size of examples tackled (flowsheets up to 16 units for the multi-floor case) and the computational requirements.

8.1.2 Safe Process Plant Layout

The objective of this stage was to develop mixed integer optimisation models by incorporating safety aspects within single-floor plant layout problems.

Two general mathematical programming formulations have been proposed to consider simultaneously single-floor process plant layout and safety aspects. The developed models determine the detailed process plant layout (coordinates and orientation of each equipment item), the number and type of protection devices in order to reduce possible accidents and the financial risk (including risk of accidents at a unit and propagation risk of the accidents to other units). Both models are based on the work of Papageorgiou and Rotstein (1998) in order to capture rectilinear-type (Manhattan) distances and rectangular footprints following current industrial practices. The first model (MINLP model) calculates the propagation financial risk by applying the equivalent TNT method (Lees, 1980) and the second one (MILP model) by utilising the areas of exposure for each item, using the Dow Fire and Explosion Index System (1994). The models applicability was demonstrated by an Ethylene Oxide Plant example. For both models, it was shown that the installation of protection devices at the most dangerous items reduced significantly the total plant layout cost despite the purchase cost of extra protection devices.

8.1.3 Simultaneous Layout, Design and Operation

Here, the plan was the development of a single-level mathematical model that would capture layout, design and planning/scheduling aspects suitable for pipeless batch plants. The resulting model should consider all components simultaneously thus resolving various trade-offs at an optimal manner.

A unified mathematical framework has been developed considering the above issues for pipeless plants based on the continuous-domain model of Papageorgiou and Rotstein (1998). It is compared favourably to literature representations (Realff *et al.* 1996) as it can decide upon the type of layout (*e.g.* Circular, Herringbone, Linear). The model maximises the income from product deliveries by taking into consideration material transfer cost and an annualised capital cost of the processing stations and the transferable vessels subject to balances on the number of vessels and the materials held in storage and layout constraints (equipment orientation constraints, non-overlapping constraints, distance constraints). The applicability of the model has been illustrated with one literature example.

8.2 Recommendations for future Work

The research presented in this thesis has identified a number of issues that need to be further investigated in order to develop efficient optimisation-based algorithmic methods for the solution of the complex mixed-integer optimisation problems, which result from our recently proposed mathematical framework for the process plant layout problem.

8.2.1 Iterative Solution Approach

In chapter 5, an iterative solution approach for the multi-floor process plant layout problem was proposed outperforming simultaneous and decomposition approaches by reducing computational requirements without significant compromise of the solution quality. For the solution of the subproblem, an alternative scheme was applied by solving a number of smaller versions of the subproblem. A number of insertion rules are followed in order to augment the set of items for which the subproblem is solved each time. For example, the inserted new items are connected to the items of the previous iteration while a maximum number of inserted items is imposed. When all the items of the chosen floor are considered, we are moving to a neighbouring floor.

Although the above iterative solution scheme has performed satisfactorily for a number of examples with flowsheets up to 16 equipment items, further improvement can still be achieved so as to allow us to tackle even larger examples of industrial interest while maintaining enhanced quality of the final solution obtained. Therefore, further investigation is required to select appropriate initial equipment set and insertion rules during the solution of the subproblem, which should enhance the overall performance of the above iterative approach.

In addition, it is envisaged that the above procedure will be enhanced by developing a post-processing phase which should attempt to improve the solution obtained. So, this phase can be analytical or optimisation based which can be applied either separately for each equipment item or group of items. After examining all flowsheet equipment, the post-processing phase can be repeated until no further improvement in the objective function is achieved. The efficiency of the post-processing phase should alleviate the computational effort required by the iterative approach by terminating the branch-and-bound procedure prematurely while a series of optimisation-based post-processing phases could finally obtain a solution of enhanced quality.

8.2.2 CLP and Hybrid Approaches

Mathematical programming models that include disjunctive constraints, such as the non-overlapping constraints in the layout problem, usually make use of big M formulations, which frequently suffer from poor linear programming (LP) relaxation. However, disjunctions can be treated efficiently by constraint logic programming (CLP), which is a discrete optimisation technique that is based on implicit enumeration and variable reduction through constraint propagation. For this reason the scope of solving the process plant layout problem by CLP (commercial and research-based) techniques as well as the combination of mathematical programming (e.g. MILP) and CLP techniques should be investigated.

Hybrid solution schemes have successfully been applied to other process systems engineering problems with disjunctive constraints such as production scheduling Harjunkoski and Grossmann (2002) by combining the strengths of MILP and CLP techniques.

8.2.3 Symmetry

As already mentioned earlier in the thesis, the three solution approaches for the multifloor process plant layout problem provided degenerate optimal solutions for the instant coffee and the ethylene oxide plants. In the models described in this work, several symmetric solutions can be obtained for every example. The number of degenerate solutions increases the computational time for the solution of such problems as branch-and-bound solvers can waste useful time to explore alternative symmetric solutions. Therefore, ways to reduce the problem symmetry should be investigated. Research should be focused on constructing partial convex hull representations for the disjunctive constraints and new selective branch-and-bound schemes.

8.2.4 Pipe Routing

In all the approaches presented in this thesis the assumption of rectilinear distances between items has been adopted. A process plant layout issue not considered here is the pipe-routing. Pipe routing provides a first pipe design at an early stage of the plant design. Although it is not as detailed as the final one it gives a realistic routing for the main pipes and most important a realistic estimation of the total piping cost which can affect dramatically the allocation of units in the land area. So far, pipe routing aspects have received very little attention (Schmidt-Traub *et al.*, 1998; Burdorf *et al.*, 2002).

A detailed pipe routing consideration may require a redefinition of the position of the connectivity inputs and outputs for each item. Here, we assumed connectivity through the geometrical centres of the items but alternative inputs and outputs should also be considered (see for example Barbosa-Povoa *et al.* 2001) for more accurate representations.

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