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MULTICRITERIA PLANT LAYOUT
WITH
EVALUATION BY SIMULATION

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MULTICRITERIA PLANT LAYOUT WITH EVALUATION BY SIMULATION

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1. INTRODUCTION

The material handling costs of a production operation are a large percentage of the total production costs. Because of this, procedures for arranging the departments of a production plant in a cost effective manner have been investigated extensively.

Early solution procedures use one of two approaches. The first is to maximize an adjacency rating based on an ordinal desirability of adjacency scale. The other approach focuses on minimizing material handling costs calculated by using a centroid-to-centroid distance metric and assuming the cost-of-flow between each two departments is a known constant. With the advent of the computational power afforded by greater accessibility to computers, researchers began incorporating greater realism in the procedures explicitly. Technical constraints such as noise levels, sufficient safety, and electricity access were considered. The mathematically defined objective functions for some more recent methods involve multicriteria, such as minimizing material handling cost *and* maximizing an adjacency rating. Few techniques utilize anything but an approximate, expected material handling cost evaluation. A few research efforts have incorporated stochastic demand and multiple demand periods in layout optimization. While production systems are evaluated with dynamic performance measures, arrangement procedures have not considered dynamic measures in their evaluations. A few researchers have begun to suggest that, because of the importance of dynamic measures, simulation should be used to verify layouts produced by their methods.

No detailed methodology for automatic generation of a computer simulation model of a production system for use in the evaluation of a particular plant layout has been documented prior to this work. Simulation has certainly been used in production system design; however, simulations are developed for a specific arrangement. Alternate solutions are developed on a trial and error basis and require explicit changes to the model. Using simulation allows for a tremendous amount of analysis that is not considered in traditional solution approaches. Rather than just expected costs, variability of the costs can be measured. The effects on cost of the variability of the demand and the changes in demand over time can be analyzed. The costs calculated can be based on time, true material movement distance, or some other function of the material handling system. Other performance measures besides cost can be utilized for comparison, such as work-in-progress queue lengths, job tardiness, and material handling system utilization.

This research effort incorporates an evaluation by simulation in plant layout optimization. The cut tree is used as the underlying structure of material handling cost optimization. Approaches based on the cut tree, including this one, have shown success in minimization of material handling costs using a form of aisle distance metrics. Once departments' spatial arrangement are determined, the details (e.g., machines, production policies) of the departments are connected and a simulation model is generated. Research by the Advanced Modeling Methodologies (AMM) group at Oklahoma State University and the University of Oklahoma provided a foundation for the implementation of the methodology developed in this work. The modeling environment developed utilizes the object oriented paradigm; the separation of information, physical, and control simulation components concept; and an execution tool-independent framework. These features enable the development of automatic simulation model generation

A new methodology for plant layout optimization is specified with analysis demonstrating its advantages. A computer implementation of the new methodology is outlined.

2. THE PLANT LAYOUT PROBLEM

The plant layout problem (PLP) addresses the spatial arrangement of the departments of a manufacturing plant or other organization. Ultimately, the goal is an arrangement of departments which aids the operation of the system (e.g., production processes) being designed or redesigned. Since a major, if not majority, percentage of production costs can be attributed to the cost of material movement, the first approaches at developing solution methodologies for the PLP utilized objective functions focused on minimizing material movement costs. More recent techniques have incorporated technical constraints explicitly and/or considered multiple objectives in the optimization function.

In some situations, the building dimensions or space available is given. In other situations, there is more flexibility in the shape of the plant. Plant layout problems include designing systems from scratch as well as re-laying out a portion of a plant. Especially, but not solely, in the case of relayout, there may be several technical constraints. These constraints may include availability of utilities or machine lubricant. For some applications, the size and shape of the departments may be predetermined, but in other cases, some level of flexibility in shape is allowed.

The plant layout problem as addressed in this research has as its objective to develop an effective arrangement of departments within a discrete part manufacturing plant. The application area is limited to discrete part manufacturing to facilitate automatic generation of simulation models by the proposed solver. The proposed solver will utilize, in objective functions, performance measures which evaluate industrial production systems of this type.

Layout from scratch and relayout will be possible with the proposed methodology. Department shapes may be fixed or rectangles with a specified range for length to width ratio. The available space within the plant must be specified, although there may be more space available in the plant than the total area required by the departments to be located. Since relayout is possible, the ability to specify departments' locations and/or shapes is allowed.

Previously proposed and available solution methodologies approach the PLP from various angles. Different procedures incorporate constraints and objective functions in alternate fashions. Plant layout optimization tools, however, are not yet evaluating alternative arrangements based on the true effectiveness of a layout for a particular production system. Simplifications of the objectives are developed which are addressable by optimization techniques and heuristics. These efforts have certainly been valuable. The pursuit of truer measures of effectiveness of a layout, however, seems a worthy effort.

Truer measures of effectiveness include the following:

1. *Accurate material handling cost.* Currently, most techniques measure material handling as a function of distance such as: $COST_{MH} = \Sigma_{ij}\, c_{ij}\, f(d_{ij})$ where c_{ij} is the cost-of-flow between department i and department j and d_{ij} is the distance between department i and department j. This distance is typically rectilinear, $d_{ij} = |x_i - x_j| + |y_i - y_j|$, or squared Euclidean, $d_{ij} = (x_i - x_j)^2 + (y_i - y_j)^2$, where (x_i, y_i) is the centroid of department i. Centroid-to-centroid distance is an approximation which assumes that material moves from locations which are randomly and uniformly distributed across departments. c_{ij} is a constant. This assumes that the cost-of-flow is certain, unchanging and linear with respect to distance. Hence, most techniques operate on an expected value of material handling cost objective. Many situations exist where distance is not uniformly

distributed. In addition, the cost-of-flow is not always linear. For example, for a neighboring department, push carts may be used to move material. If the same two departments were to end up highly separated in a layout, however, a fork truck might be used. Thus, actual material handling cost is often discontinuous and nonlinear with respect to distance. Techniques which model cost in this manner would be of benefit.

2. *Material handling system utilization.* Certain arrangements of departments may minimize the total distance traveled by material. The current material handling system, however, may not be able to accommodate high localized traffic. Thus, while material movement cost appears low in total, there may not be good utilization of the entire material handling system.

3. *Flow Time.* Production systems can be designed to optimize a variety of performance measures. The effect of layout on these measures is rarely considered in layout optimization routines. (A link is indicated by the recent development of new production system designs—e.g., dedicated JIT lines, group technology.) A plant layout solution tool which evaluates a traditional production system performance measure along with material handling costs would have value. Note, at a minimum, such a tool would be a good research tool for testing the correlation between material handling cost optimization and optimization of other traditional production system evaluation criteria.

4. *Work-In-Process.* Similar to flow time, the amount of work-in-process is used to evaluate production system, but is not traditionally used to evaluate spatial arrangements.

5. *Variation in Performance Measures.* As discussed in (1) above, most techniques optimize expected values. There is a great amount of variability in most production environments. Demand is not certain and is changing over time. Processing times have a stochastic nature for a variety of reasons.

Possibly most critically, however, for layout evaluation, is that the material handling system will experience variability. Some arrangements may cause greater variability in the utilization of the material handling system. Blocking of aisles, especially with AGVs may be problematic for certain layouts. While the stochastic nature of demand has been addressed in a couple of recent research efforts, no layout optimization routine has evaluated variability.

This research demonstrates the feasibility of connecting a simulation evaluation with a layout optimization tool. No methodology for this had been previously presented in the research literature. Such a solution tool would bring the field of plant layout closer to determining effective layouts for a production system.

Simulation was chosen because of its demonstrated performance in evaluating manufacturing systems in the past. Simulation can model a rich amount of detail and is the most popular technique for situations involving variation and complex interactions. Simulation has not been used, however, as a part of a layout optimization routine. This research demonstrates that this is possible.

3. LITERATURE REVIEW

This chapter reviews the key research literature on automated plant layout solution approaches related to this effort. The solution approach developed in this effort is unique compared to existing research. In addition, this research effort answers questions which have been raised in the recent literature.

Methods for solving the plant layout problem (PLP) have been based on a variety of techniques. Summaries are found in Meller and Gau (1996-2), Francis *et al.* (1992), Tretheway (1992), Sule (1988), Kusiak and Heragu (1987), and Foulds (1983).

3.1. OBJECTIVE FUNCTIONS

This section describes the material handling objectives which have been used in PLP solution approaches. No documented efforts consider dynamic performance criteria in analysis.

3.1.1. Expected Material Handling Distance

The first objective function formulated for an automated plant layout solution approach is: Min $\sum_{i,j} c_{ij} f_{ij} d_{ij}$ where c_{ij} is the cost of moving a unit of material a unit of distance between department i and j, f_{ij} is the expected flow between department i and j, and d_{ij} is the distance between department i and j (Armour and Buffa, 1963). This objective function considers only the expected material movement cost. The metric is based on expected values and models long term performance. Although some recent efforts (Benson *et al.*, 1997; Tretheway and Foote, 1994; Kim, 1992) have utilized material flow along aisles, the vast majority of efforts assume material flow originates and terminates uniformly across departments.

3.1.2. Expected Savings from Adjacency

A body of research in automated plant layout is based on Muther's Systematic Layout Planning technique (1961). The vast majority of these techniques use approaches based in graph theory (Carrie et al., 1978; Foulds and Robinson, 1978). The objective used is: Max $\sum_{i,j} r_{ij}x_{ij}$ where r_{ij} is the savings achieved (Meller and Gau, 1996-1) if departments i and j are adjacent in the layout, and x_{ij} is a binary variable indicating whether or not department i and j are adjacent. This metric ignores the relationships between departments which are not adjacent in a layout.

3.1.3. Hybrid of Distance and Relationship Based Metrics

Some researchers have used a combination of the Expected Material Handling Distance and the Expected Savings from Adjacency objectives (Urban, 1987; Badiru and Arif, 1996). Meller and Gau (1996-1) show that layouts used by either objective function are reasonably robust to the other.

3.1.4. Traditional Simulation Output Results

Simulation has been used effectively as a tool for comparing manufacturing system designs Law and Kelton (1991, page 2), Chierotti and Rozenblit (1992), King and Fisher (1986), Turner *et al.* (1978, page 357). Pratt *et al.* (1993) state, "[Simulation] is perhaps the only viable tool for analyzing the detailed dynamic behavior of large complex systems." Pritsker (1992) deems simulation as a premier technique to determine "...time-varying characteristics important to solving the problem..." Norman (1992) notes simulation's past success as a planning tool in manufacturing environments and that it will grow to become central to manufacturing firms daily operational planning and control.

The use of simulation as a factory layout design tool is not considered in the standard texts of plant layout. Francis *et al.* (1992) does not mention computer simulation as a tool. Sule (1988) presents simulation as a technique for choosing the order of entering departments for a construction technique. Simulation *is* mentioned by Sule as a system *evaluation* tool in his chapter on material handling system design.

Thus, simulation, while being recognized as a leading analysis tool for complex systems, including manufacturing systems, has not been incorporated as part of layout optimization routine for the purpose of dynamic system performance evaluation. That is, there is no documentation on successfully using simulation as part of an interchange technique.

3.1.5. Summary

Used separately, or in combination, the expected material handling distance and adjacency savings objective functions focus on minimizing the long term costs of moving material. Some other "closeness" factors can be incorporated when the adjacency savings is used.

Simulation has been used to evaluate production facilities, but has not previously been used in the evaluation during the development of a block layout.

With WIP, flow time, and material handling system cost, material handling system utilization, and cost of utilized space as performance measures, the capabilities of this effort advance the state of the art in PLP research.

3.2. LAYOUT OPTIMIZATION APPROACHES

Given the combinatorial nature and multiple criteria evaluation of layout design as faced by practitioners in industry, automatically generating an optimal layout is beyond reasonable expectation. Many of the procedures currently available provide value as one step in the layout design process. Therefore, the methodology presented in this work, expands existing techniques for developing good layouts. The approaches utilized are discussed in this section.

3.2.1. Fixed Aisle Structure Technique

In Tretheway and Foote (1994), the FAST approach is developed based on the observation that techniques to that point provided layouts which require significant modification prior to implementation due to the lack of a logical aisle structure. Therefore, the FAST approach fixed the aisle structure before assigning departments to locations. The scatter diagram developed in Drezner (1987) is used as the basis for assigning the departments around the aisle structure.

The idea of fixing an aisle structure is used in this new methodology. In this work, however, the assignment of departments is based on a cut tree. In addition, several other extensions to FAST are present in this work: fixed locations may be specified for aisles, ranges for aisle locations may be specified, perimeter aisles may be specified, and department locations may be restricted.

3.2.2. Cut Tree Based Techniques

Since the number of departments that can be adjacent to another is limited, techniques which can quickly identify the most important adjacencies are useful. Montreuil and Ratliff (1989) suggest use of the cut tree as a basis layout development. The cut tree is particularly effective in the analysis of aisle based material flow between input/output locations on the aisles.

A cut tree is a spanning tree of the graph of all flows between departments. In particular, the cut tree is developed such that the weight of each arc represents the flow between the two sets of departments created when the arc is removed. Montreuil and Ratliff note the following: "If the aisle structure for the layout is restricted to be a tree with all aisle segments the same length, then the cut tree provides the aisle structure which minimizes the number of trips times the distance traveled." For this reason, the cut tree is used in the proposed methodology to develop layouts and evaluate them for improvement.

Banerjee, *et al.* (1992) develop a plant layout solution tool which utilize the cut tree. Their effort uses a traditional rectilinear distance based objective function and does not place restrictions on aisle locations. Two important concepts are presented which are used in this work. First, the tool developed is an interactive optimization design tool. The user uses visual tools to assist the layout improvement process. In addition, the authors identify four potentially sub-optimal conditions which are presented for the designer to consider. The *ThickLongThinShort* concept is incorporated in the methodology presented in this work. The concept itself will be discussed further in chapters 5 and 6.

3.3. SIMULATION MODELING METHODOLOGY

To achieve evaluation of dynamic system performance measures, a simulation tool for the manufacturing system is required which is easily re-configurable. In order to accomplish this, a tool independent modeling structure (Duse *et al.*, 1993) is used. In this paradigm, the components of the system are specified and manipulated independent of their use in a simulation tool. A configuration process is used to create an executable simulation model based on all or a subset of the base model.

By generating simulation models automatically just before execution, any aspect of the system being represented can be altered without making changes in the simulatable representation of that system. A highly modular approach to software development facilitates this property. Using an object-oriented programming language and structure greatly aided the development of such a software. Pratt *et al* (1993) suggest a framework in which physical, information, and control components are modeled separately. This approach to modularization is very powerful for allowing rapid generation of an experiment of simulation models.

The implementation developed in this work uses the tool-independent, modular (with separation of physical, informational, and control components), object-oriented approach, discussed above, throughout its software design.

3.4. RESEARCH GAP

No methodologies are present in the literature which handle locating departments around a logical aisle structure allowing the following constraints: fixed or restricted aisle location, fixed or restricted department shape, fixed department location.

Neither are there any methodologies presented in the literature which integrate plant layout generation procedure with a evaluation by computer simulation.

4. RESEARCH OBJECTIVES AND ACCOMPLISHMENTS

The basic research question of this effort was:

Can a multicriteria plant layout solution methodology be developed which uses simulation evaluation in the development and improvement of a production system's spatial arrangement?

By coupling a cut tree based PLP solution approach with the modeling environment framework developed by the Center for Computer Integrated Manufacturing (CIM) research group at Oklahoma State University, such a production system design tool was designed.

As discussed in Chapter 2 and further detailed in Chapter 3, the PLP has previously been defined and approached in many ways. In this research effort, the plant layout problem is defined as follows.

This list of performance criteria incorporated is given below.

1. Material movement cost
2. Material handling system utilization
3. Flow Time
4. Work-in-process queue lengths

5. Space utilization cost

The above list of performance criteria represents an advancement in criteria used in optimizing plant layouts. The following factors and constraints of the PLP are incorporated:

1. The production system explicitly models the following items:
   a) Discrete part manufacturing
   b) Process plan based job control
   c) Stochastic demand and processing times
   d) Material Handling Systems which may involve: conveyors, AGVs/ fork trucks, human powered carts---separately or in combination
2. Predetermined department locations may be fixed.
3. Departments with predetermined shapes or departments as rectangles with restrictions on minimum lengths and widths must be specified.
4. Material flow for fork trucks/AGVs is modeled explicitly with flow on aisles.
5. Aisle may be modeled as having single or bi-directional traffic flow.
6. Aisle locations may specified as fixed or a range of locations may be specified.

The above considerations are enough to demonstrate the feasibility of incorporating simulation evaluation in a plant layout solver. With the above considerations, sufficient detail and information is given to model a production system with much greater precision and realism than has been demonstrated in the past.

In creating this methodology, the following accomplishments were achieved:

1. *Development of a modeling structure for representing a particular layout of a production system.* This structure connects individual departments to the material handling system quickly and clearly represents the specific arrangement under consideration.
2. *Expansion of the OSU modeling library of primitives for the Base Model.* These additions especially include the structure of (1) above and material handling system capabilities.
3. *Expansion of the OSU simulation modeling libraries.* Similar to (2) above, additions were necessary in the simulation module to incorporate the material handling systems included. Several enhancements were subsequently required in the statistic collection objects as well.
4. *Development of a user interface for specification of the material handling system.* An interface was developed to specify the parameters of the aisle structure, the material handling devices, the restrictions on departmental areas, and input of the associated costs.
5. *Implementation of a cut tree generator in the object oriented environment.*
6. *Development of a cut tree-based layout solution tool.* This solution tool is based on the "aisle structure" concept of FAST.
7. *Development of a framework and implementation for controlling and organizing the layout analysis and improvement process.* This tool includes data structures for storing layouts with characteristics, analysis capabilities, and user interfaces.
8. *Development of a tool to guide the analyst in the improvement process.* This module uses analytical and visual techniques to assist the user in improving the layout of the production system.

5. RESEARCH METHODOLOGY

This chapter presents the proposed multicriteria solver for the plant layout problem. The chapter begins with an overview of the proposed methodology. The remainder of the chapter further describes each major step.

5.1. OVERVIEW

The framework, at an aggregate level, is:

1. Specify the structure and the product demand of the plant.
2. Generate a flow matrix from the bill of materials and routings and calculate the cut tree.
3. Generate a layout.
4. Configure a simulation experiment and execute.
5. Review the results of the experiment
6. If a satisfactory layout(s) has been generated, then the procedure may stop, otherwise the improvement module is called for suggestions and the procedure continues with Step 3.

The steps of the framework are further detailed below.

5.2. STEP 1: PLANT INFORMATION SPECIFICATION

All information needed to simulate the manufacturing system being designed or redesigned must be input. The information required is:

- Bill of materials structure
- Plant dimensions
- Plant control (logic to use at decision making points)
- Plant departments with the following detail
    - Area and shape restrictions
    - Processes in department
- Material handling devices with the following detail
    - Distribution of speed
    - Parts which can be moved and its capacity
- Inventory policy parameters for purchased material
- Lead time distribution for purchased material
- Inventory policy parameters for finished goods
- Demand distribution
- Product routings
- Aisle structure
- Cost factors

When specifying aisle structure, the following information is provided:

- The number of aisles and their orientation (i.e., east-west versus north-south)

- The range of legal locations for each aisle (can be a fixed location or minimum and maximum)
- The width of each aisle
- The direction of flow along the aisle (or specify as bi-directional)
- For each section created by the aisles, the following must be provided
    - The number of sub-aisles
    - The range of legal locations for each aisle
    - The width of each aisle
    - The direction of flow along the aisle (or specify as bi-directional)

The following cost factors are specified by the user:

- Dollar value of an available unit of area
- Annual cost of operating each material handling device
- Variable cost per unit distance of operating each material handling device

Examples of the interfaces which collect information about the manufacturing system are given in Section 6.1.6. This section presents and describes the key interfaces related to the layout generation capabilities of the solver. The user must specify mutually exclusive departments which partition the plant area. These partitions will be referred to as "departments" or "PhysicalOrgGroups" throughout this work. Information regarding these departments is collected via the PhysicalOrgGroup Interface (see Figure 5-1). From the PhysicalOrgGroup Interface, the "Layout Const" button opens a screen allowing input of the information used by the layout generation routines (see Figure 5-2). The fields are described in Table 5-1.

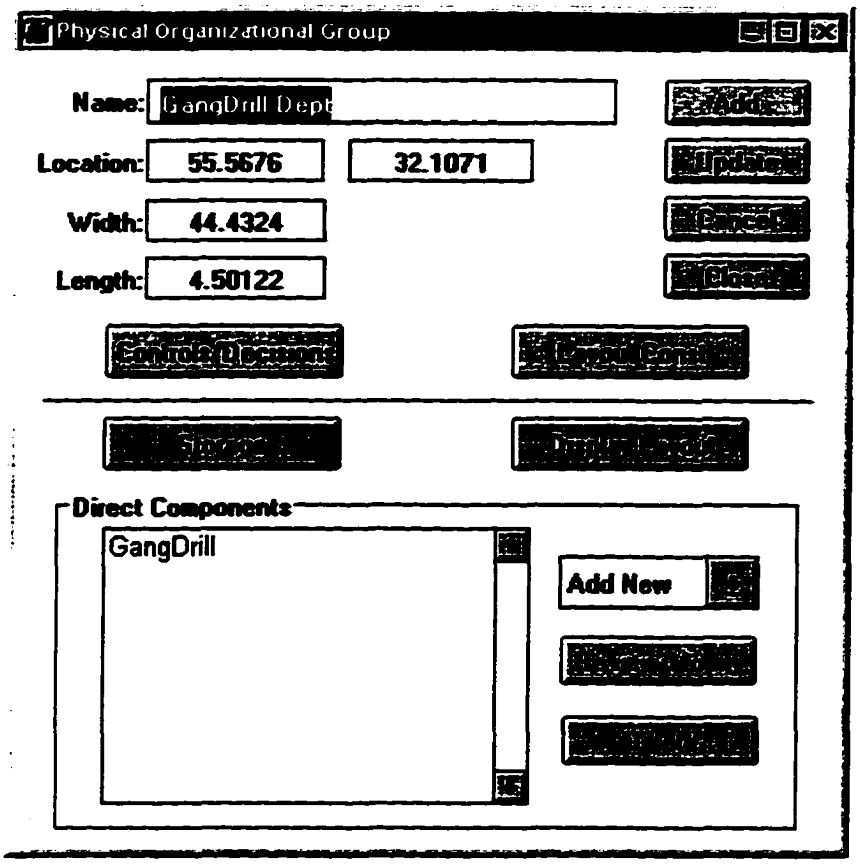

Figure 5-1: Department Interface

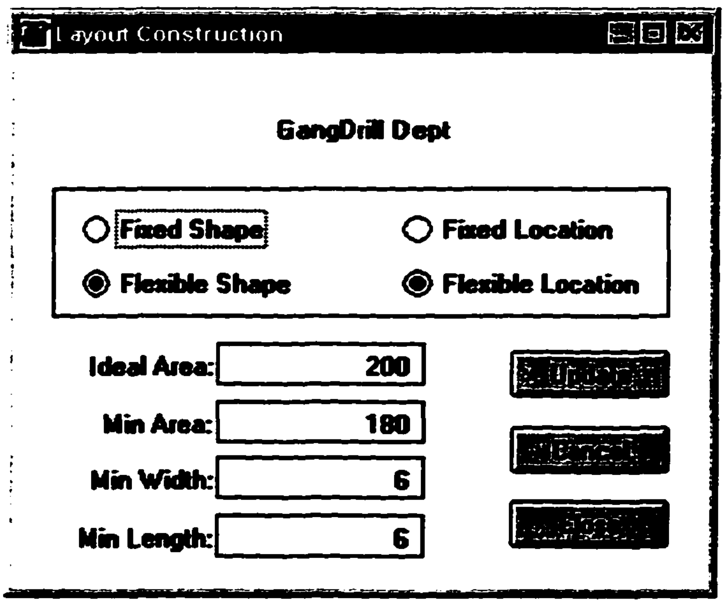

Figure 5-2: Layout Construction Parameters

Table 5-1: Layout Construction Fields

Field	*Description*
Fixed/Flexible Shape	If "fixed" shape is selected, then the dimensions of the department will be preserved. If "flexible" shape is selected, then the dimensions of the department will be ignored.
Fixed/Flexible Location	If "fixed" location is selected, then the location of the department will be preserved. If "flexible" location is selected, then the location of the department will be ignored.
Ideal Area	The layout generation procedure attempts to reserve this area for the department in question.
Min Area	If the layout generation procedure cannot find sufficient area to location the ideal area, then the area requirements will be relaxed to the min area as required.
Min Width	Minimum distance required by one dimension of the department.
Min Length	Minimum distance required by the other dimension of the department.

Another key interface related to this layout analysis tool is the specification of the material handling devices. Figure 5-3 shows an example of this interface. The user determines the type of device (fork truck/AGV, conveyor, or push cart). The speed, as a probability distribution, is specified as well as the capacity of the device. The capacity must be specified for each item that the device can handle. The units of the capacity parameter is based on the type of material handling device and is displayed on the screen.

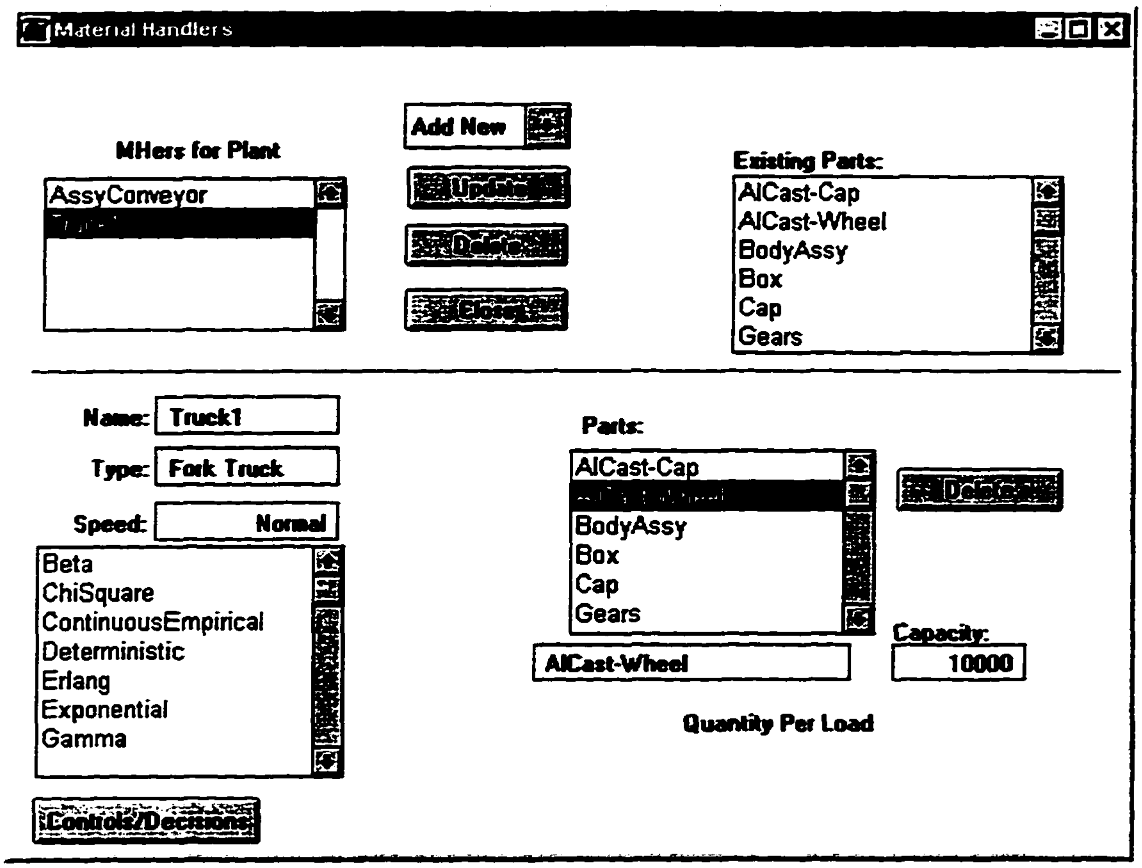

Figure 5-3: Material Handlers Interface

One of the features of this methodology is its focus on costs. In order for cost analysis to be performed, the user must specify certain cost factors. These include the value of an available unit area of floor space, the annual cost of operating each material handling device, and the variable cost based on distance traveled by each material handling device.. The interface used to collect this information is shown in Figure 5-4.

The structure of the aisles is entered through the Aisle Structure Interface (see Figure 5-5). The user specifies the number and the orientation of the aisles (North-South versus East-West). Each aisle can be configured as fixed at a location, or flexible within a range of locations by specifying a minimum, maximum and target location. The user also specifies the width of each aisle. The main aisles divide the plant into *sections*. The right side of the Aisle Structure Interface is used to input and review information regarding these sections. The "Info" button uses the aisle location information specified on the left side of the screen and calculates the resulting ranges for each section. The "OK" button displays another interface screen similar to the left side of the Aisle Structure Interface on which the user specifies information about the sub-aisles in the selected section.

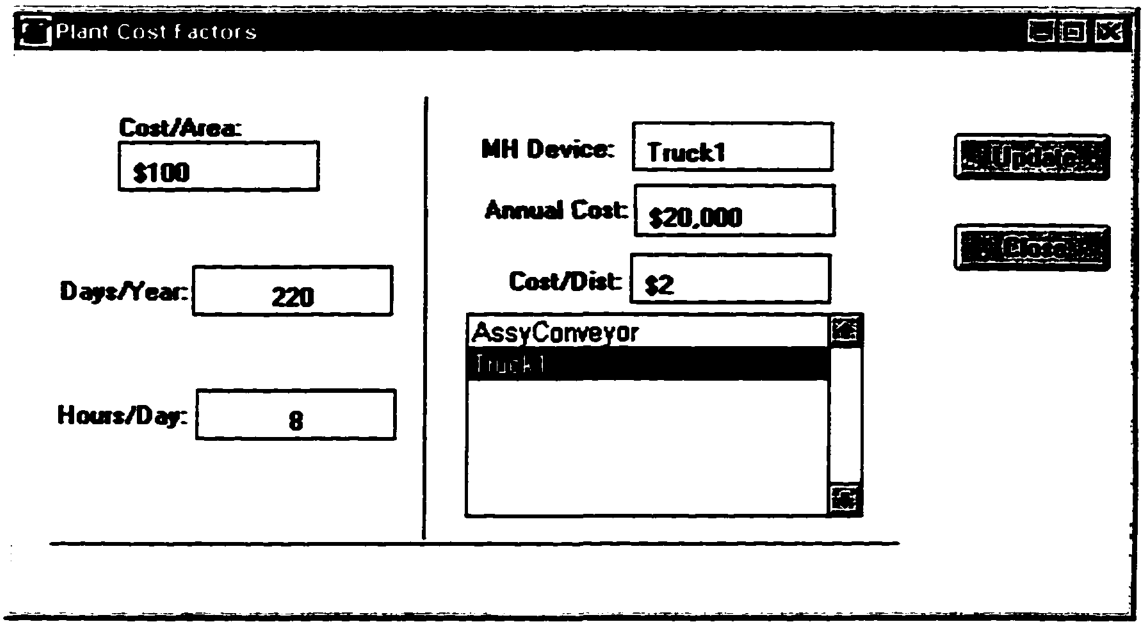

Figure 5-4: Cost Factors Interface

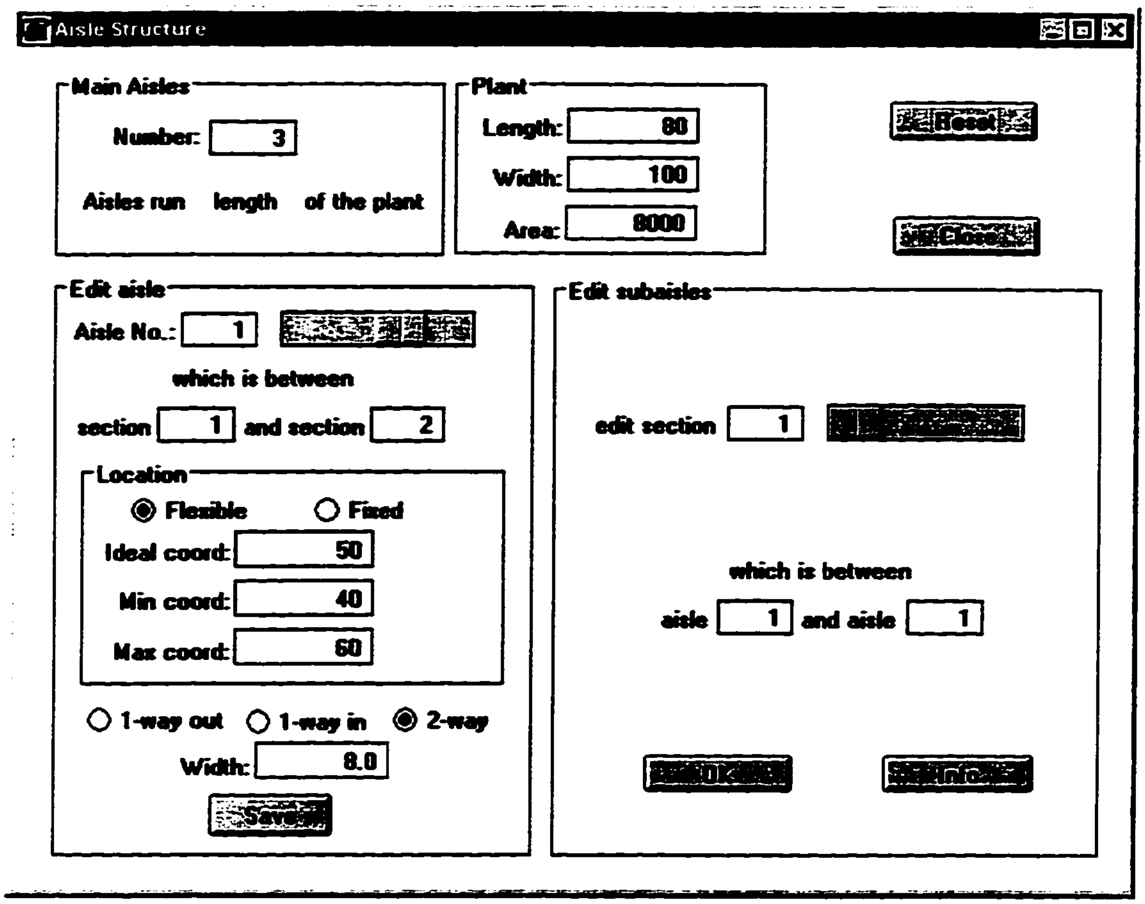

Figure 5-5: Aisle Structure Interface

This data structure for this "aisle structure" is hierarchical. The plant is organized by an aisle structure which includes partitions called sections. These sections are then each organized by a sub-aisle structure having sub-aisles and subsequent sub-sections.

5.3. STEP 2: CUT TREE GENERATION

This module averages material handling costs and calculates average flows from the product demand information. Product demand distribution mean estimates are used along with the bill of materials and routing information. This interdepartmental flow matrix is converted to a graph where the arcs represent the nonzero matrix entries. Once the graph is determined, a cut tree for the graph is generated. The calculation is demonstrated by the following flow diagram.

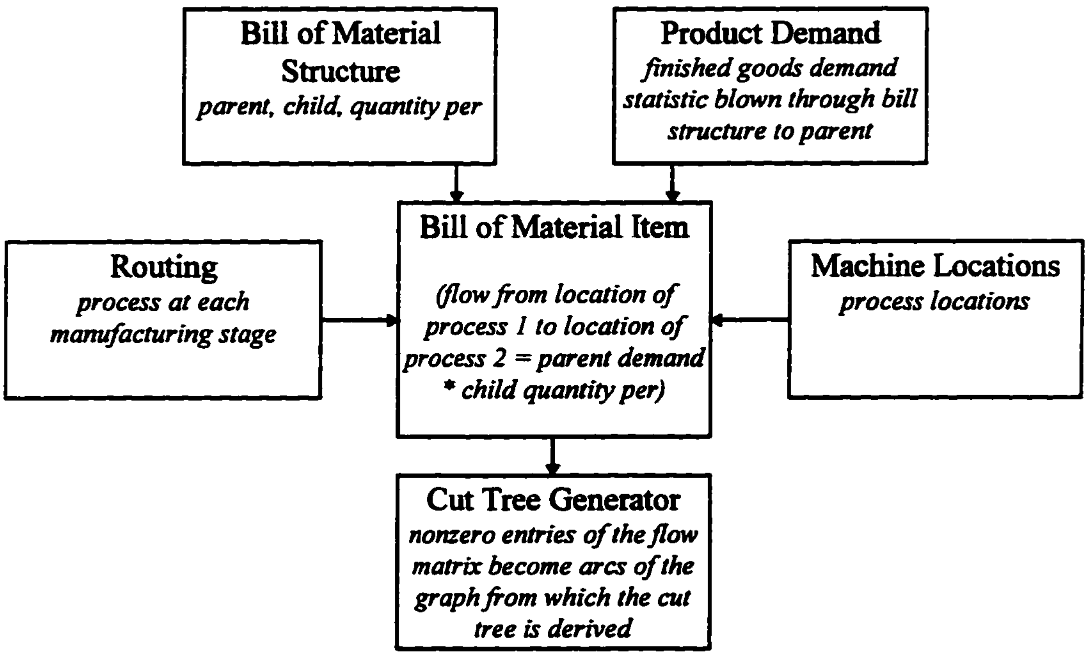

Figure 5-6: Cut Tree Calculation

In SmallTalk (Goldberg and Robson, 1989), the programming language used, an instance of the object CutTree takes the graph developed from the flow matrix, referred to as "originGraph" and determines the nodes and arcs of itself, a cut tree:

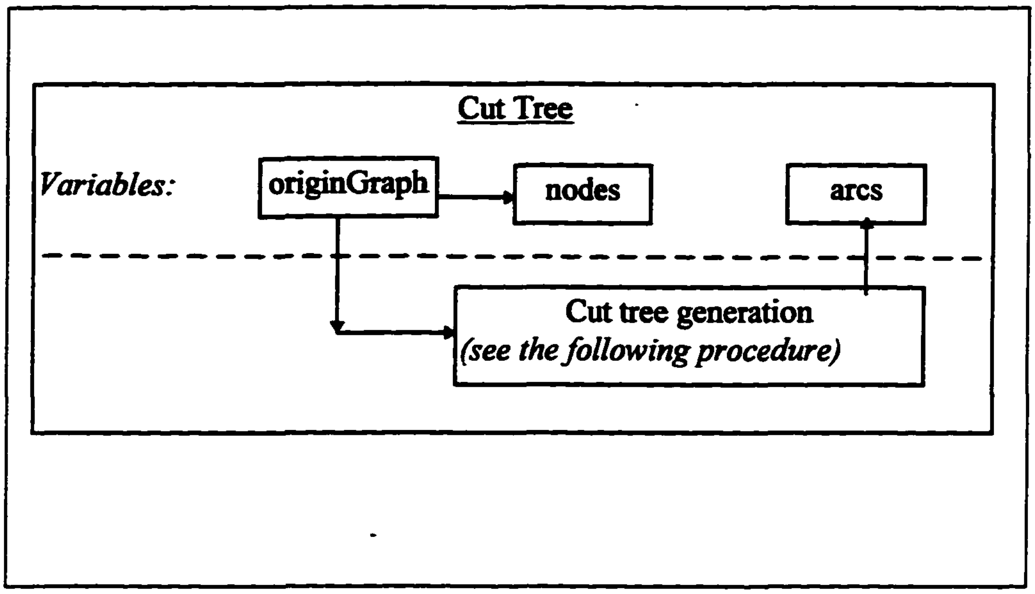

Figure 5-7: Cut Tree Object Representation

```
Cut Tree Generation Method Outline:

nodeSet ← nodes of origin Graph.
T ← any node from originGraph.
nodeSet ← nodeSet - {node of T}.
while (nodeSet is non-Empty)
{
nextNode ← any node from originGraph which is not in T.
nodeSet ← nodeSet - {nextNode}.
let T ← current tree
        while (cardinality{T} > 1)
        {
        minArc ← an arc from T which has the minimum weight of all arcs in T.
        Na ← a set of nodes from originGraph containing the head of minArc and all other nodes from
                originGraph which are one the same side of the graph as the head of minArc when a
                min cut set of originGraph separating the head and tail of minArc is determined.
        Ta ← the subset of Na which are members of T.
        if (Na includes p) then T ← Ta otherwise T ← complement of Ta.
        }
attachPoint ← singleton node of T.
cutTree ← cutTree plus the arc (nextNode, attachPoint) with weight equal to the minimum cut
        separting nextNode from attachPoint in originGraph.
}
report cutTree
```

Figure 5-8: Cut Tree Algorithm

The algorithm above in Figure 5-8 is based on the procedure presented in Ahuja, *et al.* (1993). The minimum cut and its associated value is generated based on the Preflow-push algorithm, also described there.

5.4. STEP 3: LAYOUT GENERATION

At this point in the algorithm, the following information is known and used in the generation of a layout:

- Plant dimensions
- Departmental area requirements and restrictions
- Aisle structure and aisle location restrictions
- Departmental location restrictions
- Cut tree

The procedure uses an hierarchical process to assign the departments to areas of the plant. This methodology uses the same terminology as FAST (Tretheway and Foote, 1994). The plant area is divided into contiguous areas which are distinguished by main aisles, which run the length or width of the plant. These divisions of the plant area are referred to as *sections*. Similarly, each section is divided into *subsections* by *subaisles*.

The solver has the capability of generating a layout from scratch. This includes beginning without any departments assigned as well as starting from a partial solution, or a plant which has fixed departments. These departments may or may not have a defined flow relationship with other departments. This construction procedure is presented next with a discussion of the improvement procedures presented later.

Each department which has a fixed location is assigned to an appropriate section/subsection combination. When aisle locations are highly flexible, this process is not direct. Aisles which are not fixed at this stage, are assumed to be at their target location for the purpose of assigning a department to a section/subsection. It seems reasonable to expect many aisles to be fixed when department locations are fixed. In a re-layout situation, a significant portion of the aisle structure is likely to be fixed. That is, a sufficient layout can be developed without re-designing the entire aisle structure. This solver does, of course, allow for consideration of a complete re-layout, but the amount of flexibility in the number of departments which can be relocated and the flexibility in aisle location are naturally correlated. An infeasible setup will cause a message to be displayed to the user at the point the layout generator fails. This message describes the problematic situation to the user and stops the layout generation process.

Once the pre-determined assignments are made, the area currently assigned to each section/subsection is calculated. The procedure then uses the cut tree to assign departments to sections. Once all departments have been assigned to sections, then the assignments are further refined to include specification of subsections. The following two procedures are available in the solver for layout generation. The layout generation portion of the solver is referred to as CT-FAST.

5.4.1. Largest Arc Weight with One Assigned End Point

The principle which is used to assign departments to sections in this procedure, LAWF, is as follows. Select the unassigned department which has the highest cut tree arc weight with a department which is already assigned. Then, attempt to locate it as close to that department as possible given the previous assignments to sections. The procedure starts with the section to which its "high arc weight" neighbor is assigned and then alternates between the sections on either side of the primary section, moving farther from the primary section as required. The procedure begins by assigning a center node of the cut tree to the center section of the plant to initiate the process.

Once the assignments of departments to sections is determined, the subsections are assigned in a similar fashion. To start the procedure for sections with no fixed departments, a node which has farthest distance from the center of the cut tree is assigned to the first subsection in the section. This algorithm is summarized in Figure 5-9.

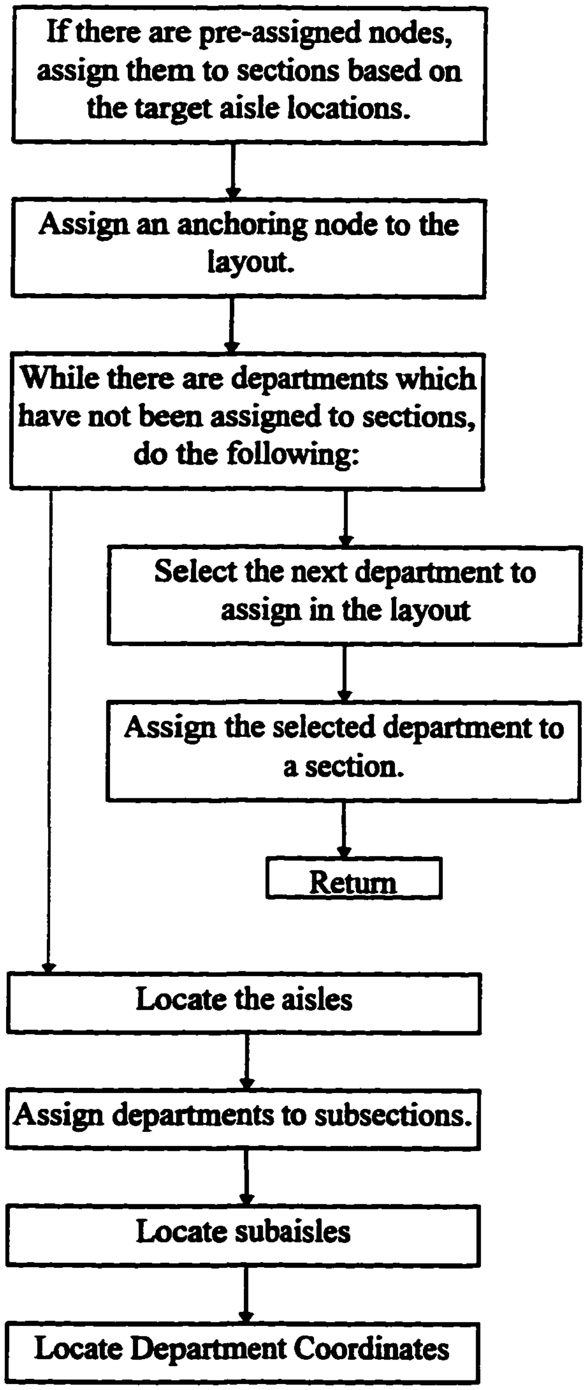

Figure 5-9: Layout Generation Procedure Outline

The details of the procedure are now outlined further. The aisles are assumed to be at their target location for the purpose of assigning the fixed departments to sections. The procedure compares the centroid of the fixed location department and assigns it to that section which contains the centroid.

A node is then selected as an anchor. For this technique, any "heavy" center node may be used. A "heavy" center node is a center node of the tree such that after removing all arcs joining two center nodes, the heavy center node is associated with the subtree having the greatest number of nodes. The anchor node is placed as close to the center of the layout as possible given any fixed departments.

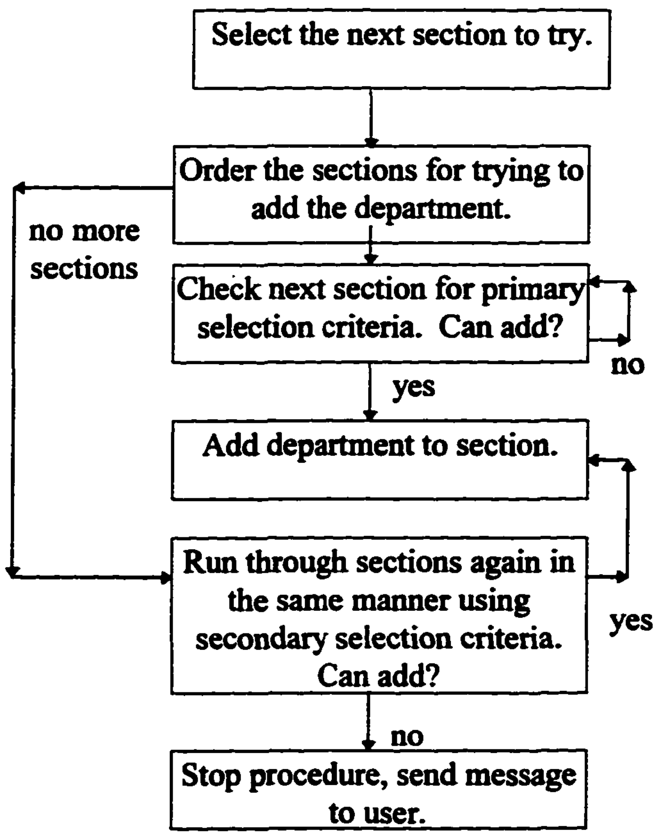

Figure 5-10: Assignment of Departments to Sections Procedure

The procedure for assigning departments to sections is outlined in Figure 5-10. The center section is tried first and if the department cannot be located there, sections on either side of the center are alternated moving farther away from the first section tried.

There are four primary criteria used to determine whether or not a department can be added to a section.

1. Is there enough available space in the section for the department's *ideal* area to be added?
2. Is the section wide or long enough to support the minimum dimension of the department?
3. Do the currently assigned departments' areas add to less than the target area for the section?
4. If half of the area of the department were added, would the section still be at or below the target area for the section?

If no section is selected after having tried all sections, then a second pass is made through the sections (in the same order). On the second pass, the following secondary selection criteria are used for testing.

1. Is there enough available space in the section for the department's *minimum* area to be added?
2. Is the section wide or long enough to support the minimum dimension of the department?

If no section can accept the department, then the procedure stops and a message is sent to the user.

After the anchor department is assigned, the next department to add must be determined. The next department to add is determined by dividing the departments into two sets: Set-A contains the departments already assigned, Set-B contains the departments which still need to be assigned. Of the arcs of the cut tree which connect Set-A to Set-B, the arc with the highest weight is identified, say Arc(i,j). The endpoint in Set-B of Arc(i,j) is the next department to add. The first section to be considered in trying to add that department is the section containing the endpoint of Arc(i,j) from Set-A.

Once all departments have been assigned to sections, the aisles which border the sections must be determined. The aisles are located starting at one side and moving across the plant or section. To begin, the first perimeter aisle is located. Its width defines one side of the first section. As the procedure locates the second the aisle, the coordinates of the first section are determined. Therefore, the procedure works on the "next" aisle at the same time as the "prior" section.

The procedures for main aisles and subaisles are identical. Main aisles are located within the plant and subaisles are located within the confines of a section. Since the section is of fixed dimension when the subaisles are located, the procedure is the same.

When calculating a "test" location for an aisle, there is a three phase process. The first phase of the algorithm is as follows:

test_locn(i) ← (aisle_location(i-1)+aisle_width(i-1)/2) + (assigned_area / plant_side - subaisle_widths)

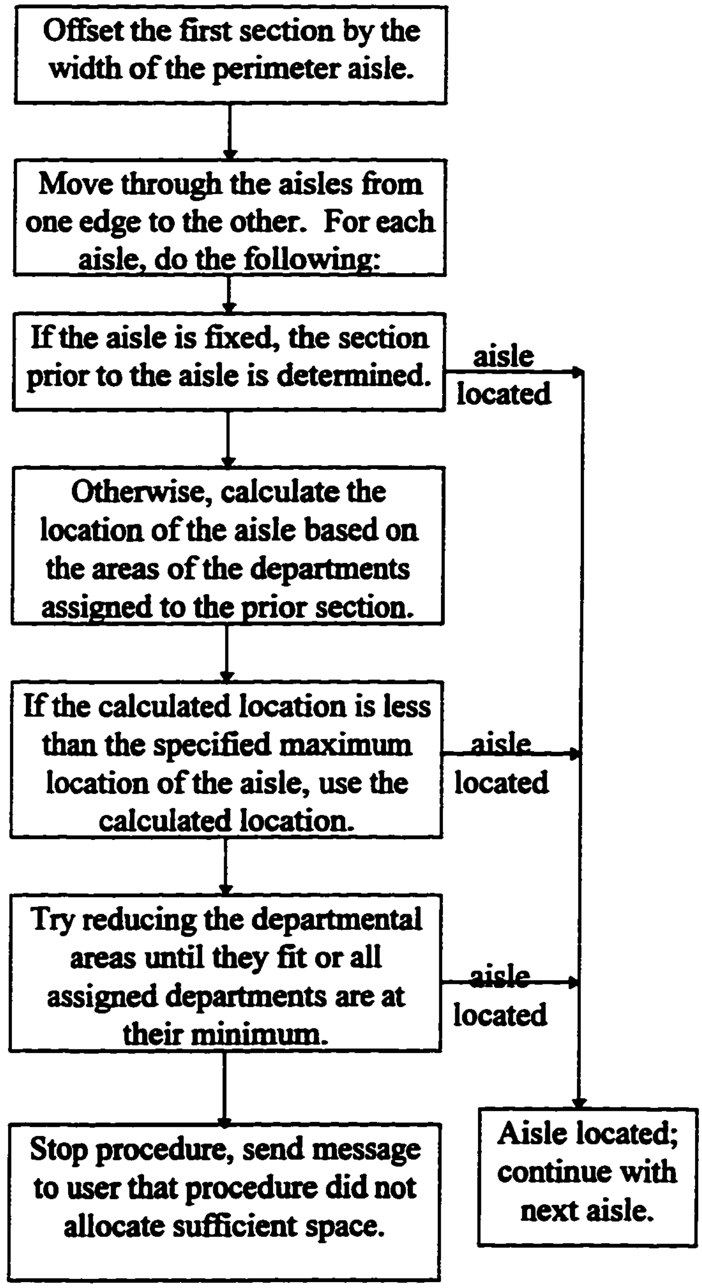

Figure 5-11: Aisle Location Routine

In the formula, subaisle_widths is the sum of all the widths in the section in question.

The plant_side is the *length* of the plant if the aisles run lengthwise and the *width* of the plant if the aisles run widthwise. For assigning subaisles, subaisle_widths is always zero and plant_side is the appropriate side of the section.

The second phase of the algorithm is to ensure that the section can handle any fixed departments. This is done by inflating the section (or subsection) until the full length/width of any fixed departments are accounted for. A section which is 10 units wide might have a fixed department which is 12 units wide assigned. The subsection would be inflated to being 12 units wide.

The third phase of the algorithm is to account for the minimum dimensions of the departments. If a minimum dimension is specified, then it is possible that there will be unused area in the section. This "dead" area is calculated and an allowance is made in the test location of the aisle.

The assignment of departments within a section to subsections is slightly different than assigning departments to sections of the plant. There is a two phase process. First, an ordering of the departments that have been assigned to the section in question is made. Second, the departments are added to the subsections of that section based on that order. That is, the first department, as ordered, is placed as close to the beginning of the section as possible. Then the next in order is placed as close to the beginning of the section as possible. The selection of the subsection is the same as described before for the selection of a section. The difference in the procedures is how the next department to add is selected.

The selection of the next department to add is based on the department order. The ordering of the department is determined as follows. Since the set of departments assigned to a section may not be a connected tree, the procedure applied to assigning departments to sections cannot directly apply to the assignment of departments to subsections of a section. A simple modification of that procedure is used. The cut tree provides the maximum flow between any two nodes. Therefore, even if a set of departments assigned to a section is not connected, the set of departments can be transformed into a fully connected graph where the links represent the maximum flow between each of the two nodes. The "maximum flow" is the minimum arc weight along the path connecting the two nodes in the cut tree. Using this graph describing the maximum flows, the same procedure described above for selecting the next department to add can be used.

Within the section, the departments are ordered from the middle of the section to the outsides. For example, if the departments were assigned in the order A-B-C-D-E-F, then the order in the section from left to right is E-C-A-B-D-F.

Once the order is determined, the departments may be assigned to subsections using this order. This is the same process as assigning departments to sections. Rather than selecting the next department based on an arc weight, the next department is selected in order. The first department is added to the first subsection. The next department is then added in or as close to that section as possible. This is accomplished using the same criteria that was used in the assignment of departments to sections of the plant.

The final step is to determine the coordinates of the departments. At this point in the algorithm, all aisles are in a fixed location, so each subsection of the plant becomes an independent case. The assigned order of the departments is used in determining the location. Departments may be assigned in the x-direction or in the y-direction. Note that the author intuitively prefers ordering the departments between subaisles. That is, if the difference in the subaisles locations is the x coordinate, then the departments are assigned from minimum x to maximum x.

To determine the location of the department, the following algorithm is used:

1. Let the set *F* be all the fixed departments.
2. Let *d* be the next department from the assigned department order in the subsection.
3. Divide the area of department *d* by the width (length) of the subsection. If the length (width) as calculated violates the minimum dimension constraint of *d*, then let the length (width) equal the minimum dimension and calculate the width (length). In this case, the width (length) of the department is less than the width (length) of the subsection creating "dead" space in the layout.
4. Determine the trial coordinates of *d* assuming that the origin of *d* is at the origin of the subsection.
5. Determine if the coordinates of *d* violate any department in *F*. If not, the department is located; if there are no more departments to locate, stop; or if there are more departments, continue with step (6). If there is a violation, continue with step (7).
6. Add *d* to *F* and continue with step (2).
7. Locate *d* such that it is just beyond the department in *F* which intersected the current coordinates of *d*. That is, slide the *d* further along in the subsection until the bottom border of *d* is the same as the top border of the department in *F* which caused the violation.

8. Continue with step (5).

If there are fixed location departments, then there is a good chance that the procedure will fail to fit the departments into the layouts. When this happens, the difference in the calculated area required for the section and actual area required by the fit is determined. The section and the "next" aisle are adjusted to account for this area. Then, that section and the subsequent sections in the layout are re-assigned and located. The procedure continues with the location of departments until either the coordinates of all the departments are calculated, or the layout is stopped due to the failure of the procedure to handle the fixed department. Fixed departments will not be much of a problem if they are along the perimeter of a section and plant.

The procedure as described above will meet the constraints placed on the aisle and department locations and shapes. These restrictions, however, may cause a failure to fit even though there is a feasible solution. That is, this is a heuristic procedure. Continuing to handle more difficult fit problems is left for future research. Lin *et al.* (1996) discuss the failure to fit issue and offer three procedures for relaxing shape constraints to find a fit. In addition, these procedures provide an excellent starting point for resolving the "dead space" issues created in this research. The interchange portion of this methodology, however, does allow the user to perform department interchanges and moves which open up the possibility of generating layouts that the procedure cannot find.

To further explain this procedure, an example is described now. The cut tree which was generated for the example is shown in Figure 5-12. The areas of the departments are shown in Table 5-2.

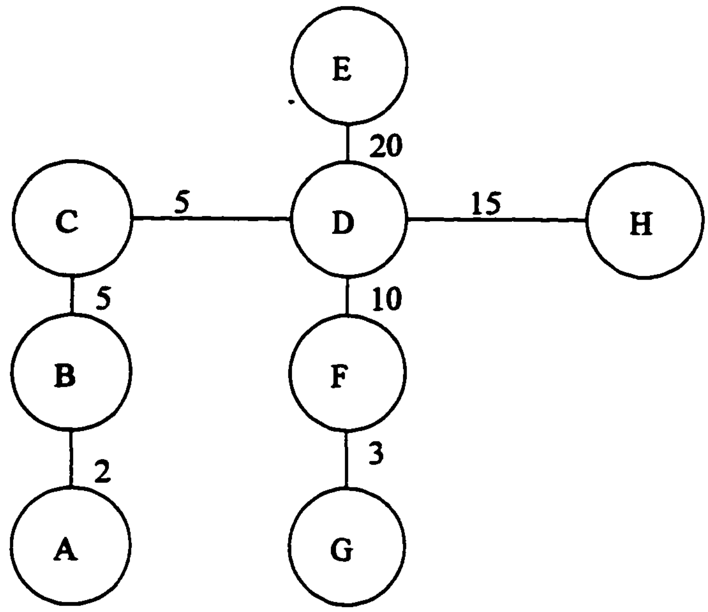

Figure 5-12: LAWF Example Cut Tree

Table 5-2: LAWF Example Data

Department	Ideal Area	Min Area	Min Dim	Min Dim
A	200	200	5	5
B	100	100	5	5
C	100	100	5	5
D	300	300	5	5
E	200	200	5	5
F	200	200	5	5
G	300	300	5	5
H	100	100	5	5
TOTAL	*1500*	*1500*		

The dimensions of the plant for this example are 60 wide by 40 long. There is one main aisle running the width of the plant. It should be located between 15 and 25 with a target of 40. One section has no subaisles. The other has two subaisles with the following restrictions (min., max., target): (10, 30, 20) and (30, 50, 40). The width of all aisles is 10. For illustration, the unassigned departments are represented by {UAD}; the assigned departments by {AD}; the sections by {Si} for i=1,2; the main aisle by {A}; the subsections by {SSi,j} for subsection j in section i; and the subaisles by {SAi,j} representing subaisle j in section i.

The heavy center in the example is D. Assign {S1}={D}, so {AD}={D}. Consider the arcs connecting {UAD} and {AD} and select the arc with the highest weight. In this case, that is Arc(D,E). Try to assign E to the section containing D. It can be assigned: {S1}={D,E}; {AD}={D,E}. This process continues the assignments are {S1}={D,E,H,F,C} and {S2}={}. The next department to enter is B. The total assigned area in {S1} is 900. With an {A} location target of 20, the target area for {S1}=900. Therefore, the department cannot be added to {S1}, so the next section, {S2} is tested for assignment---which succeeds and {S2}={B}; {AD}={D,E,H,F,C,B}. This process continues until all departments are assigned to sections of the plant. This results in the assignments {S1}={D,E,H,F,C} and {S2}={A,B,G}.

The next step is to assign the aisles. The total area assigned to {S1} is 900. Since 900/60=15, the test location for the section is 15+width/2=20. This is between the maximum and minimum aisle locations, so it is accepted. {S2} then begins at 20+width/2=25. There is no other main aisle, so the boundary of the last section is based on the plant boundary. The plant with aisle {A} is shown in Figure 5-13.

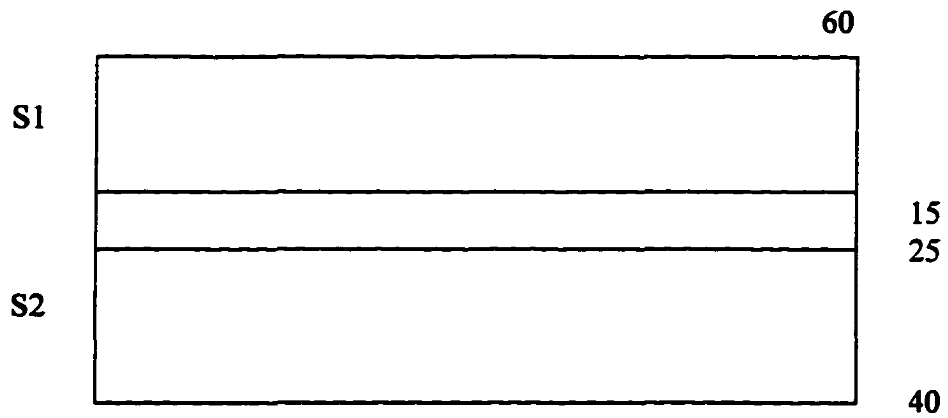

Figure 5-13: Plant with main aisle located

Each section is now handled separately. For the departments assigned to {S1}, an order must be determined. Per the algorithm, the department which is in {S1} and closest to the center of the cut tree is first. Then, the department with the maximum flow, according to the cut tree, with an assigned department is chosen next. For the example, this leads to an order of D-E. The next department to be added is added to the beginning of the order (e.g., H-D-E). Then the next department is added to the end of the order (e.g., H-D-E-F). The ordering continues in this fashion, alternating between adding to the end of the order then to the beginning of the order. For the example, the final order is C-H-D-E-F. Similarly, the order for {S2} is A-B-G.

Once the order of the departments is determined for each section, the departments must be assigned to subsections. Since there are no subaisles, and therefore no subsections for {S1}, this step is skipped. For {S2}, the criteria used for assigning departments to subsections is the same as that for assigning departments to sections. The order of assignment is important, since it will be used to locate the coordinates of the departments. Department A is assigned to {SS2,1}. The target area for section {SS2} is 225 (15x15). Since adding department B would violate the "target symmetry" primary criteria, B is added to {SS22} (i.e., 200+100-225 is not less than 225-200). Similarly G cannot be added to{SS22}, so assignment is made to {SS23}. Note that the area required is greater than the target area, 225, but is less than or equal to the maximum area of 375 (15x(30+width/2)) Assignment of the subaisles works in the same manner as assignment of the main aisles. The results for this example are {SA21}=18 1/3, {SA22}=30.

The final step is to find the coordinates. Per the procedure detailed above, the coordinates are determined for each subsection independently using the order of the departments. Consider {S1}first. The section{S1} consists of only one subsection {SS1}. The origin of {SS1} is (0,0). The corner of {SS1} is (60,15). The first department in the order is C. The width of C is calculated by dividing its area by the section's length (e.g., 100/15) which is 6.67. The department is located at the origin of {SS1}, giving it the coordinates of (0,0)-(6.67,15). Since there are no other located departments, this location is final. The next department is H which also has a width of 6.67. Per procedure, it is located at the origin of the section giving it coordinates of (0,0)-(6.67,15). This location, however, intersects department C. The department is "slid" down the section just past department C, so that its new trial coordinates are (6.67,0)-(13.33,15). There are no violations now, so these coordinates are final. The procedure continues for the rest of {SS1}. The process is the same for {SS1}, {SS2}, and {SS3}. The final coordinates for this example are shown in Table 5-3 and a layout is shown in Figure 5-14.

Table 5-3: Final Coordinates for LAWF Example

Department	Origin	Corner
C	0,0	6.67,15
H	6.67,0	13.33,15
D	13.33,0	26.67,15
E	26.67,0	40,15
F	40,0	53.33,15
A	0,25	13.33,40
B	23.33,25	30,40
G	40,25	60,40

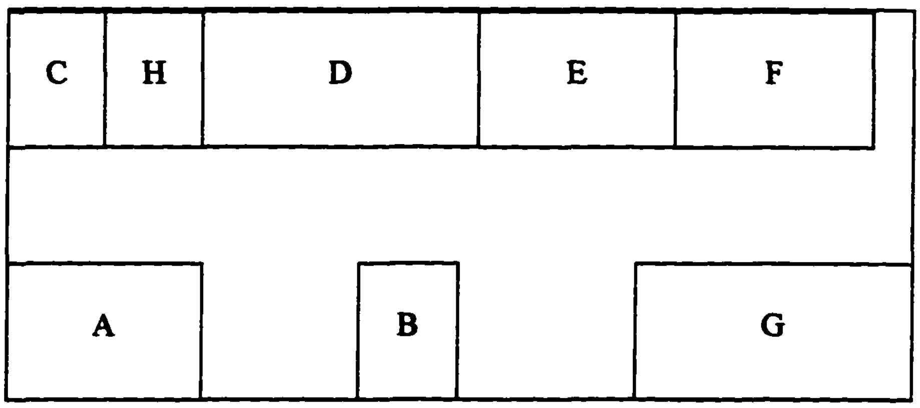

Figure 5-14: Final Layout for LAWF Example

5.4.2. Tip Node in the Corner

A second procedure is provided for algorithmically generating layouts. This procedure is basically the same as the LAWF procedure with a few modifications. Rather than working from the center of the plant to the edges of the plant, this procedure works from one corner to the corresponding farthest corner.

The first modification is that the anchor department is a cut tree tip node rather than a heavy center node. A tip node is a node having degree of one; that is, exactly one arc connects the node to the rest of the tree.

The second modification is in the ordering of the departments. There is no re-ordering of the departments after the assignment to a section. The order of assignment is used for assignment to subsections with one stipulation. The direction of the ordering is reversed in alternating sections. That is, if the first section uses the assignment order from left to right, then the second section uses the assignment order from right to left.

Consider the example from the previous section. A tip node is selected as the anchor. In the implementation developed by the author, any tip node may be specified. By default, however, the procedure selects a tip node which is farthest from a heavy center. (Distance on a tree is measured with one arc traversed equaling one unit of distance.)

In the example, department A is selected as the anchor node. It is assigned to section one, {S1}, using the same criteria as before. The assignment procedure from this point is identical to the LAWF procedure. For example, the arc with the largest weight connecting the assigned nodes (i.e., A) and the unassigned nodes is Arc(A,B). Therefore, B is the next department to enter the layout. The assignment process continues resulting in {S1} containing A-B-C-D-E and {S2} containing H-F-G.

The ordering of {S1} is simply the assignment order: A-B-C-D-E. The order of {S2}, however, is the reverse of the assignment order which results in: G-F-H. This order is used for the assignment of departments to subsections. Once the departments are assigned to subsections, the aisles are located and then the departments are located just as in the LAWF procedure. Figure 5-15 shows the layout generated for this example.

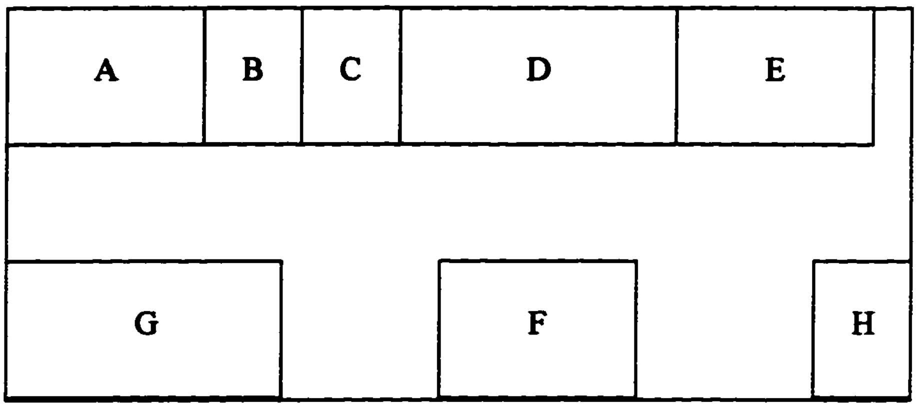

Figure 5-15: Final Layout for TIP example

The above techniques for layout construction are intended to generate good "starting" solutions. They are based on the cut tree which is based on symmetric, long term, static flow analysis. The improvement module of the solver will identify opportunities for improvement and the solver facilitates evaluation of alternatives as recommended by the improvement module or desired by the user.

5.4.3. Material Handling Locations

The next step is to determine the material handling location (i.e., door, input/output location) for each department. Two algorithms are implemented in this effort. Algorithm one determines the closest aisle to each department centroid based on perpendicular distance. Material movement through other departments is disallowed. The location for a department is a location on the closest aisle to the end point of a perpendicular line from the department centroid to the aisle.

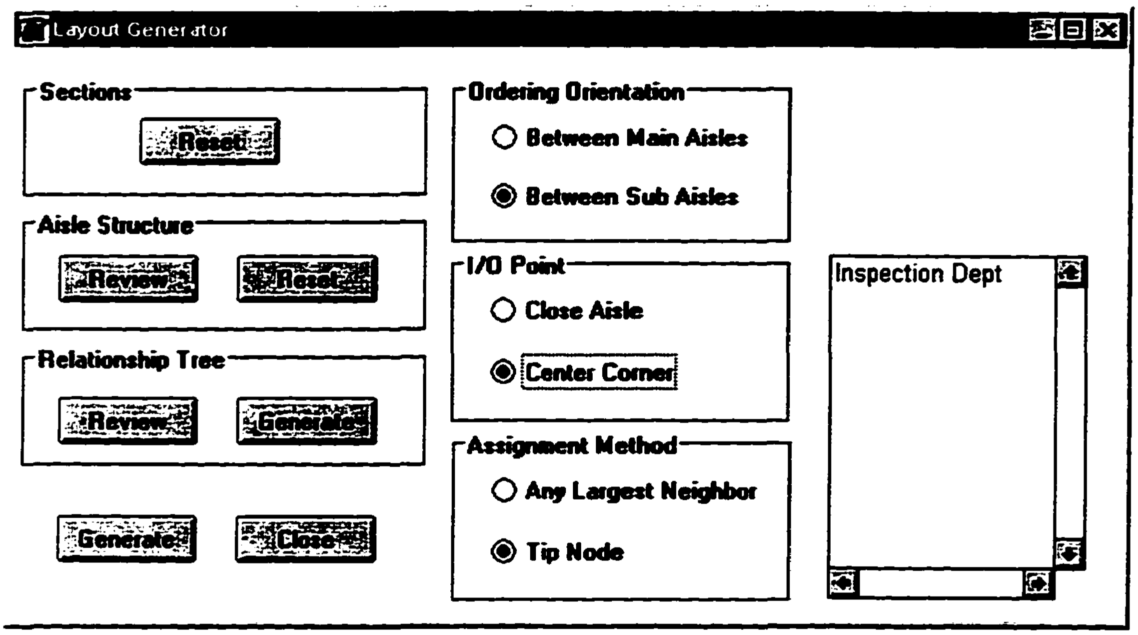

Figure 5-16: Layout Generation Interface

Algorithm two compares the corners of each department and assigns the corner which is closest to the centroid of the entire plant as the location for that department. This algorithm was used by Kim (1992).

Access to the Layout Generation step is achieved via the Layout Generator Interface (see Figure 5-16). Note that this interface provides access to the Aisle Structure Interface and the Cut Tree generation procedure as well as layout generation options selection. The user indicates which layout procedure (described above) is to be used, which material handling location procedure is to be used, and which ordering orientation technique is to be used for departments within subsections.

5.5. STEP 4: SIMULATION MODEL CONFIGURATION AND EXPERIMENT EXECUTION

Once the precise input/output locations of the departments and the locations of the aisles are determined, then the entire specification required to evaluate the system is complete. A simulation experiment is then configured. The program takes all the data specified and converts it into code which can simulate the plant activity.
A "SimAisleNetwork" is created which consists of "SimAisleSections". These aisle sections are resources which must be acquired along with a material handling device for material movement. During this configuration process, the aisle structure is analyzed by Floyd's algorithm (Ravindran *et al*, 1988) to determine the paths the material handling devices will use to navigate the structure. This is used for fork truck and AGV devices. Conveyors and Push Carts are modeled with Euclidean or rectilinear distance between input/output locations or department centroids as specified. Note that the conveyors and push carts process the material movement differently in terms of capacity and delay time. See the later sections on implementation details for further discussion on how these are modeled.

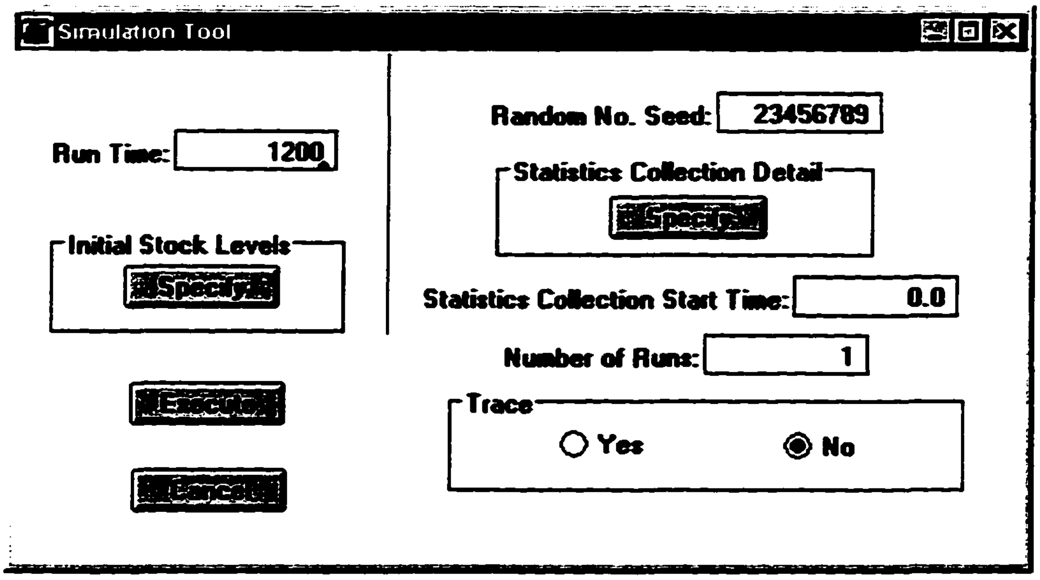

Figure 5-17: Simulation Tool Interface

Once configured, the user specifies some parameters about the experiment. Initial stock levels must be specified. They may be read from a file. The length and number of runs are specified. The level of statistic collection (summary, detailed, none) may be varied for any variables which the simulation code is capable of collecting. The main Layout Simulation Tool is presented in Figure 5-17.

5.6. STEP 5: RESULTS EVALUATION

Once the simulation experiment is complete, all the results from the simulation experiment are available for review. Built into the solver, moreover, is the capacity for collecting key metrics along with the corresponding layout and model details. This is stored for later review and comparison by the user. The metrics the implementation is currently capable of are those identified earlier in Chapter 3 of this work: WIP, MH system cost, MH system utilization, flow time.

At this point the user may alter the model and expand the simulation experiment in any way for further study and/or consider the analysis of the improvement module which may suggest improvement opportunities.

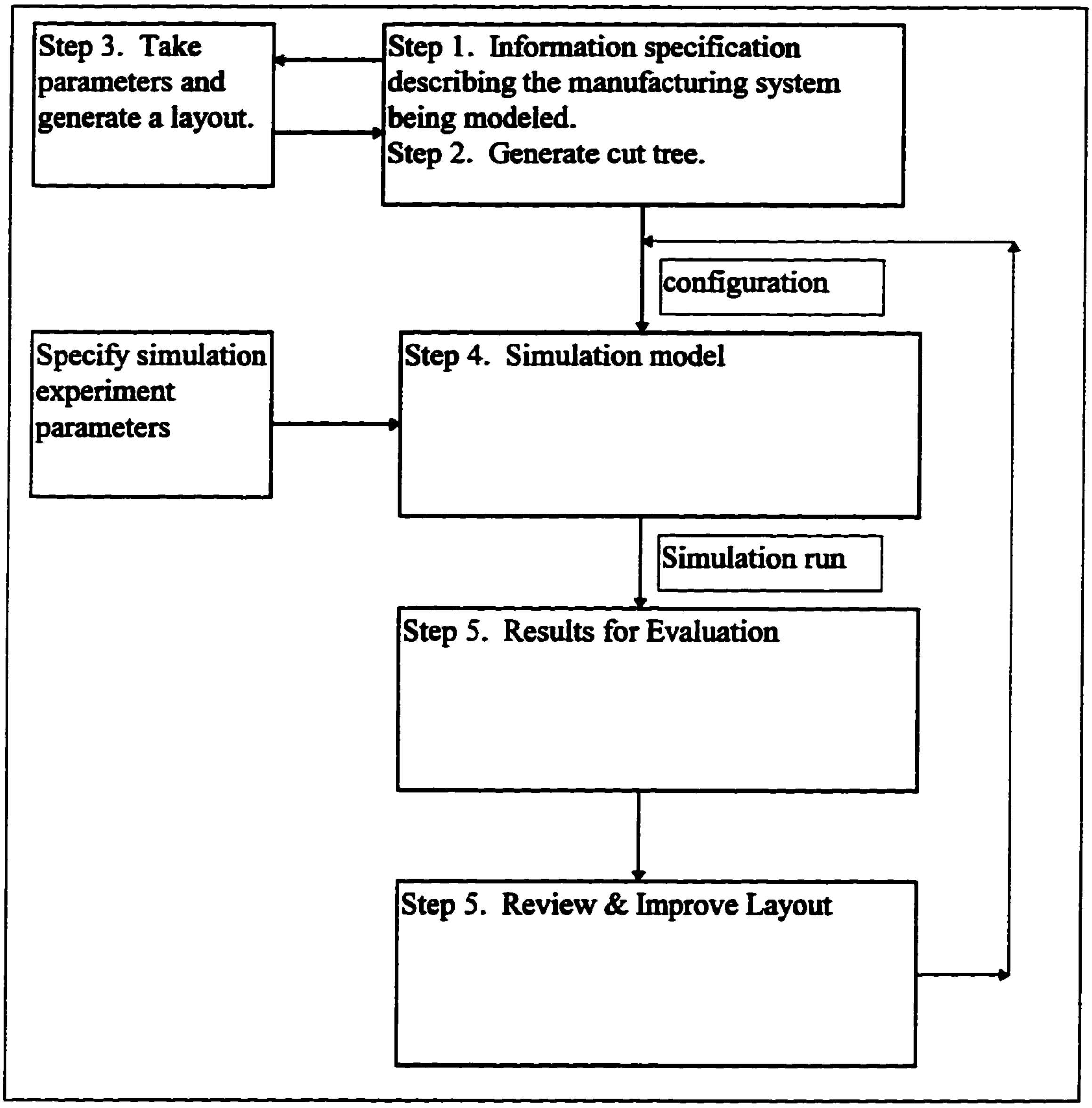

Figure 5-18: Methodology Flowchart

Figure 5-18 shows how the Simulation process fits into the overall methodology.

5.7. STEP 6: IMPROVEMENT MODULE

The improvement module is a tool to aid the user in identifying areas where there is opportunity for improvement. The tools available to the user for identifying improvement opportunities are discussed in the sections below.

The visual aids developed for the analyst are very powerful analysis tools. Scriabin and Vergin (1975) compared three computer procedures for plant layout---including CRAFT---to humans working without computer assistance. On eight problems ranging in size from 5 to 20 departments, the humans outperformed the computer algorithms at the 0.002 level. Scriabin and Vergin conclude that some of time spent by researchers pursuing fully automated layout solutions might be better spent on developing solution approaches which incorporate a human's ability to assimilate complex patterns quickly.

5.7.1. Cut Tree Graph Overlays

The methodology implementation has the capability to display the cut tree on a drawing of a given layout. There are two options for this overlay. One method uses the department centroids for the nodes of the cut tree and the other uses the material handling locations as the nodes of the cut tree.

Figure 5-19 shows a layout using the centroids as nodes. The layout drawing feature allows the user to "zoom" in and out as well as scroll around to different parts of the plant area. Note that the arc thickness' as displayed are weighted relative to each other.

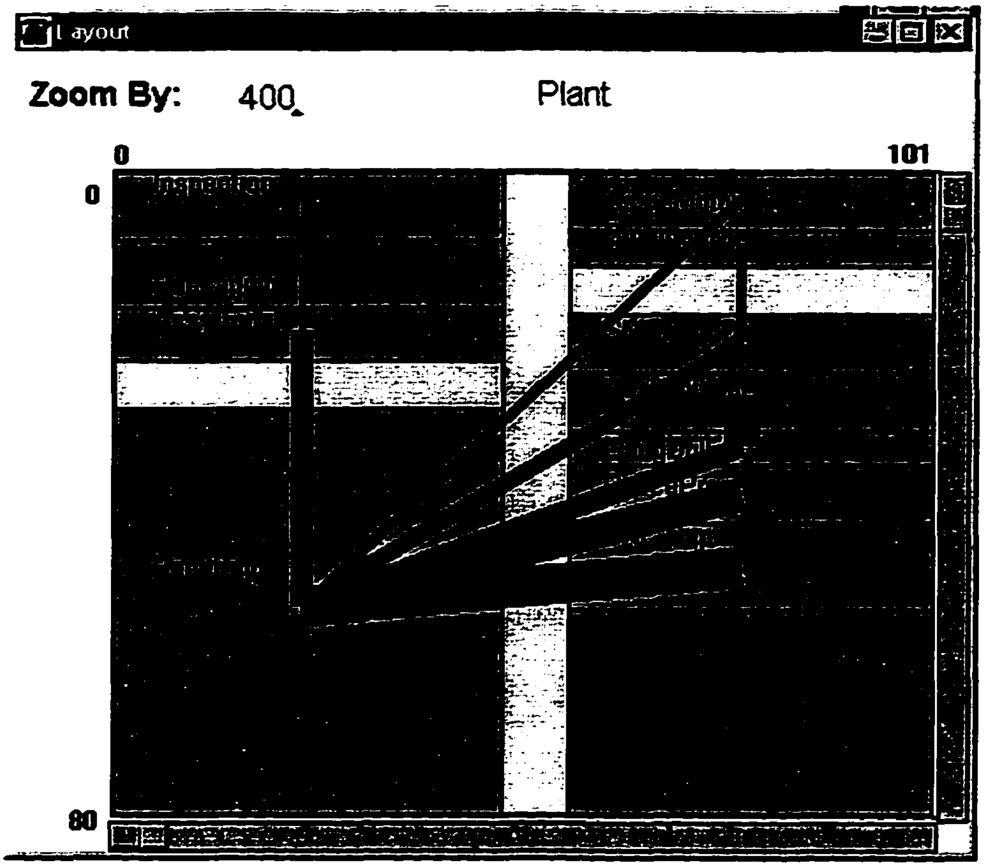

Figure 5-19: Layout with Centroid Cut Tree

Figure 5-20 presents the same layout using the material handling location based nodes.

5.7.2. Flow Direction on Aisles

One of the features of this layout solution tool is its ability to more fully model aisle flow. The traffic flow direction on an aisle can be specified or the aisle can be configured as having bi-directional flow. By explicitly modeling single versus bi-directional flow, the analyst can adjust the width of the aisles. To assist the analyst's determination of what type of traffic flow would be appropriate, the flow from the flow matrix is summarized by aisle by direction of flow. Figure 5-21 provides an example of this tool. The cost of the area gained (or lost) by changing the traffic flow direction is also calculated and presented.

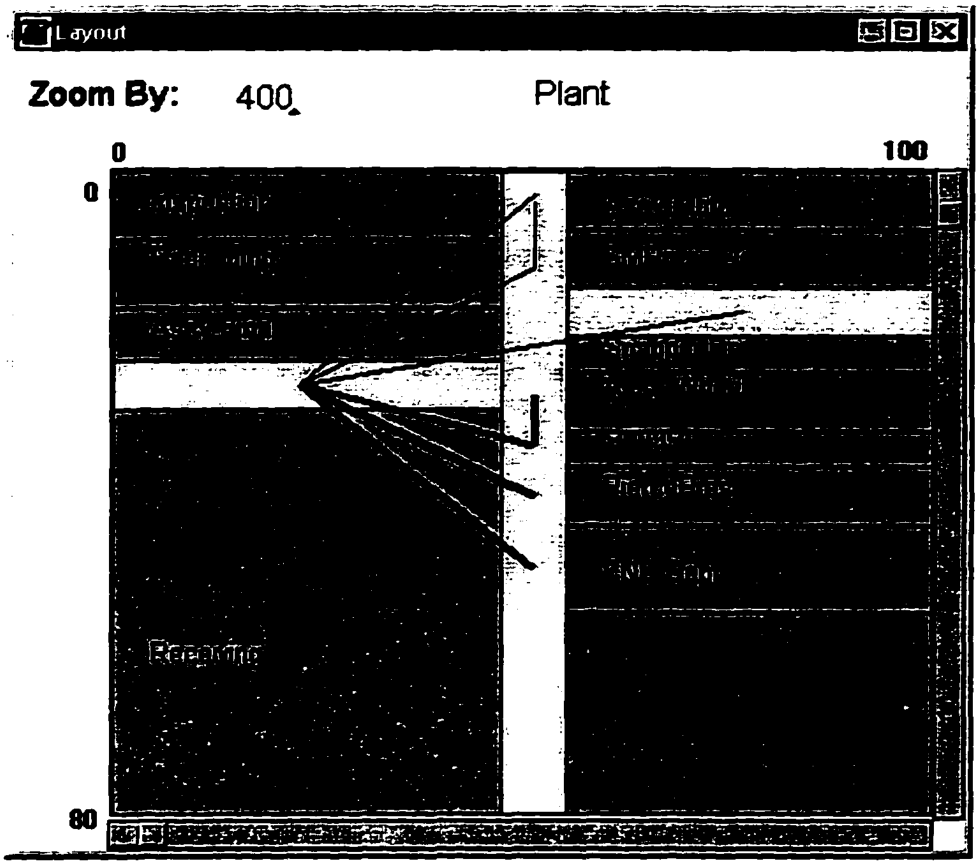

Figure 5-20: Layout with MH Location Cut Tree

5.7.3. Cut Tree Arc Crossings

The solver also calculates some departmental interchanges which may lead to improved solutions. These are particularly useful for identifying situations when a re-layout may be beneficial. That is, an existing production system will change characteristics over time, so, as demand and processing patterns change, the cut tree could be altered. When the cut tree has changed sufficiently, re-layout of the system may be cost effective.

The first of these potential improvement opportunities is identified by overlaying the cut tree on the layout and calculating the arcs which cross each other. These crossing are ranked via a potential improvement factor and displayed to the user. The implementation provides an easy interface for the user to effect the desired departmental interchange in the model. Once the layout model is altered, the user may run an simulation experiment and determine the affects of such a redesign. These interchanges are displayed to the user via the Interchange Interface.

5.7.4. Cut Tree Node Neighbor Interchanges

Another technique for identifying interchanges based on a cut tree overlay is also provided. For this analysis tool, the improvement module reviews each node and its neighbors. Each arc emanating from a node is weighted by its distance times the flow on the link. Any interchanges which would reduce the sum of the arcs weights at a node are presented to the analyst. This concept is based on the ThickShortThinLong of Banerjee, *et al.* (1992).

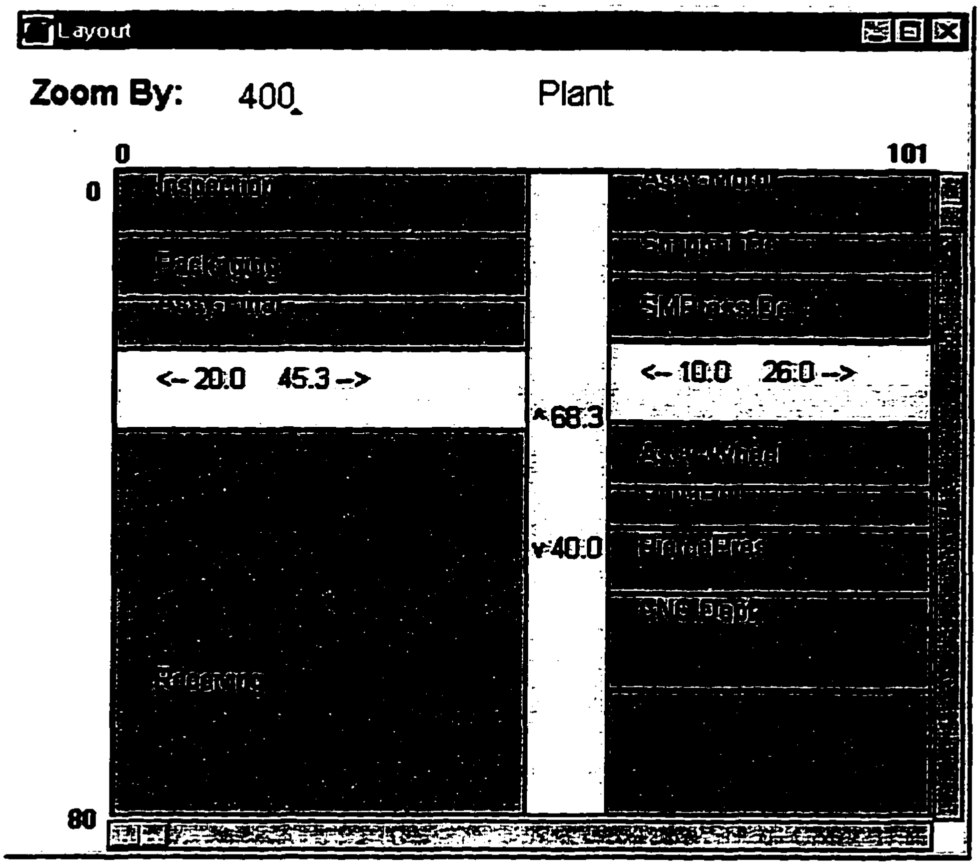

Figure 5-21: Layout with Aisle Flow

5.7.5. Layout Ranking By Selected Metrics

At the end of a simulation experiment, selected metrics regarding the layout used in the model are saved as part of the layout analysis tool. All saved layouts may be quickly ranked by one of the selected metrics. The metrics that are available include those listed in Table 5-4.

Table 5-4: Metrics Saved With Layouts

Aisle Area Cost
Available Floor Area
Available Floor Area Cost
Average WIP Level Mean & Standard Deviation
MH Operating Cost Mean & Standard Deviation
MH Utilization Mean & Standard Deviation
Utilized Floor Area Cost
Product Flow Time Mean & Standard Deviation

5.7.6. Analyst-Identified Interchanges

For the departmental interchanges and moves, the solver implementation can automatically make many changes in the layout. These can be based on recommendations from the Improvement Module or simply identified by the analyst as a configuration worth executing a simulation experiment on.

Two types of department interchange/movement are allowed: "interchange" and "move". Interchanges and moves may be made under two levels of flexibility of re-layout accommodation. The first is the most restrictive in which all aisles are frozen. In this case, other departments may move slightly based on their flexibility parameters. The second technique allows sub-aisles to be moved, but not main aisles. As in the first technique, other departments may move slightly based on their flexibility parameters.

In the case of more subtle alterations in the material handling system, the user is required to make the changes in the model input directly. An example of such a change is altering the type of material handling device used for certain items.

5.8. IMPLEMENTATION DETAILS AND ASSUMPTIONS

This section provides additional specification of how various situations are modeled, particularly in the simulation tool. In addition, other subsections provide insight on how the software code is structured.

5.8.1. Order Filling

The system implemented assumes a build-to-stock environment which uses a (*s*,*S*) inventory policy. Orders are filled from available stock. If stock is not available, the order is lost. When the level of inventory drops below a specified level, *s*, then an order is sent to the manufacturing floor for a quantity of *S* minus the current inventory level.

The control of orders on the floor is handled by creating shop orders at each level in the bill of materials. Thus, material is assembled for a particular assembly. Manufacturing of a product will not be started until all purchased material is available in the plant.

5.8.2. Material Movement Control

When material completes a process, the event is reported to the process's department. Currently, the department passes all control decisions on to the plant. While the connections exist for providing pluggable control logic at the department level, this was not seen as necessary to demonstrating the methodology. The plant's functional controller responsible for material control responds to the message that a process has completed. The logic used for making this decision is based on the user specifications in STEP 1. The controller then instructs the physical components of the plant on how to proceed.

5.8.3. M.H. System Locations and Material Movement

Material is transported from the specified input/output location for the department in which the process resides. In the case of fork trucks and AGVs, the movement is along aisles. That is, each aisle section is modeled as a resource which is obtained before travel is permitted. An *aisle section* is the largest possible portion of an aisle which contains no departmental input/output locations nor intersections with other aisles. Therefore, the endpoints of the aisle sections represent departmental input/output locations and aisle intersections. Once a request to move material has secured a material handling device, it sequentially acquires and releases aisle sections along the path that is traveled. These sections have a modeled capacity and utilization statistics are collected.

In the case of push carts, material is simply delayed across the distance required. This distance is based on the I/O locations, but travel does not require acquiring the aisle section resources; access is assumed to be available in any direction when required. The capacity on each push cart may be specified in linear feet per item.

For conveyors, the capacity of a conveyor is specified by the number of linear feet a quantity of one for each part type requires. The distance on the conveyor is calculated after the layout is determined. Material also moves between input/output MH locations.

5.9. SOLVER ENVIRONMENT

Under this framework, the analyst (say, a manufacturing engineer) is asked to specify the details of the system using *their* terminology. The analyst can evaluate the system for criteria of interest: tardiness, utilizations, material handling cost, material handling device queues. The implementation is based on the object-oriented, manufacturing system analysis environment developed by the Center for Computer Integrated Manufacturing of which this author participated (Duse *et al.*, 1993), (Mize *et al.*, 1992).

5.9.1. Object Oriented Paradigm

The highly modular nature of an object oriented environment makes possible the development of the proposed solver. The key properties of the object oriented paradigm (OOP) which are utilized in this effort are:

Data Encapsulation: In the object oriented paradigm, objects are data encapsulated by methods. *Methods* are the names of the operations, or subroutines, and are associated with a particular object class. This structure modularizes and protects the data which is beneficial in large programming efforts. In addition, this reduces the dependence of the overall program on the specific data structures chosen.

Polymorphism: With OOP, different objects may understand the same messages. *Messages* are the names of the methods which encapsulate the data. Different objects, however, may respond to the <u>same</u> message differently (i.e., they have different methods for the same message name). For example, with the proposed solver, different departments may react to the same message with alternate action.

Inheritance: The structure of computer code following OOP allows behavior to be inherited. An object's *behavior* is the methods associated with that object, so previously coded methods for an object can be automatically associated with a new object by deriving the new object for an existing object. This process of deriving objects from existing objects is known as *inheritance*. This allows objects of similar nature to share code. This is useful in this effort, since many manufacturing resources have common behavior. For example, all material handling devices are loaded and unloaded---many in the same fashion (e.g., AGV and fort truck) for modeling purposes.

5.9.2. Modeling of Control Structure

The software is designed for ease of expandability. This is important as it is beyond practicality to implement all conceivable production philosophies and practices. Particularly, in terms of decision making, the code was structured to provide maximum flexibility. Examples of these decisions include: selecting the next job to work, determining how to proceed at the completion of a job.

This goal was accomplished by separating the model of control logic from the modeling of the informational and physical components of the system (Pratt et al, 1993). Figure 5-22 shows how these components interact.

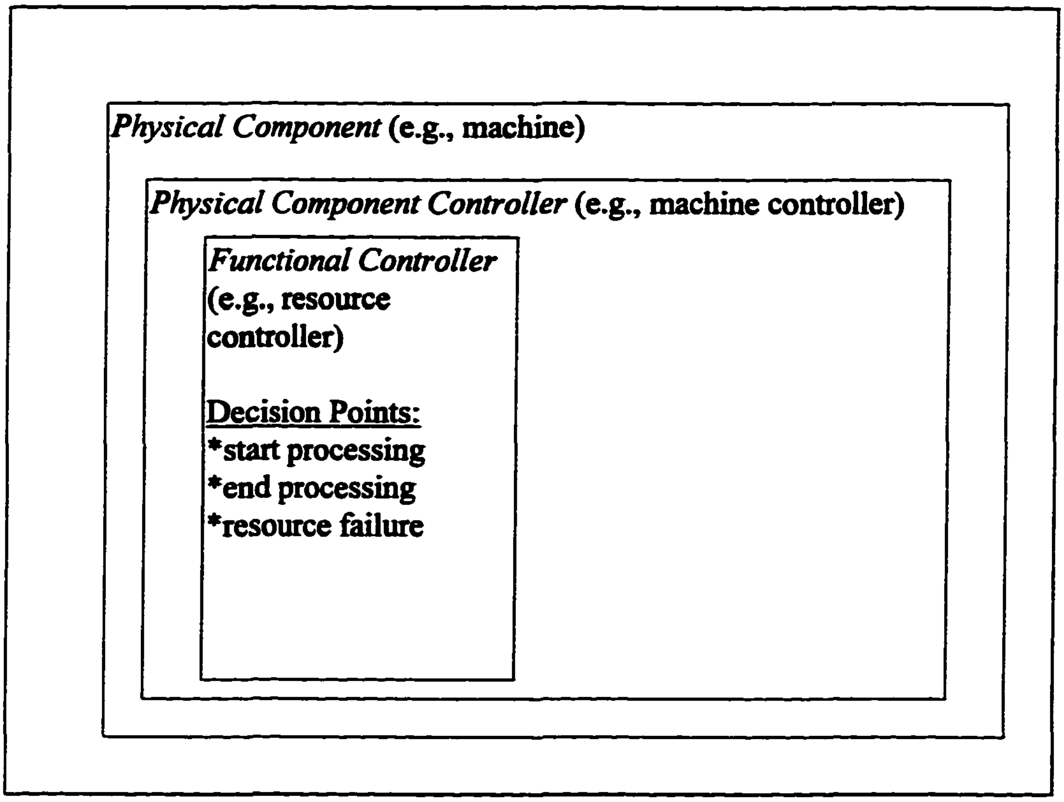

Figure 5-22: Control Modeling Structure

Not only will a physical component interface with its controller, but its controller may direct it to send a request for a decision to be made at a more global level (e.g., departmental level—which might, in turn, request a decision from the plant level controller).

6. EVALUATION OF RESEARCH

6.1. JUSTIFICATION OF LAYOUT TECHNIQUES

This section presents some examples demonstrating how the theory behind the layout techniques suggests the techniques should be successful. Given the complexity of the layout problem, the procedures cannot be guaranteed to be optimal in all cases, but the procedures are optimal for some cases presented below.

6.1.1. Example of Tip Node Layout Procedure

The Tip Node based technique for arranging departments in the plant should produce the best possible solution for a flow shop or near flow shop. The reason is that the cut tree for an *n*-department flow shop has *n-1* arcs as in Figure 6-1. Assuming the departments are equal size, the layout configurations presented in Tretheway and Foote's (1994) section on flow shops will be generated by the Tip Node layout procedure, also.

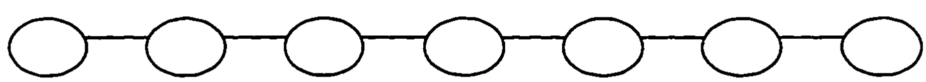

Figure 6-1: Pure Flowshop Cut Tree

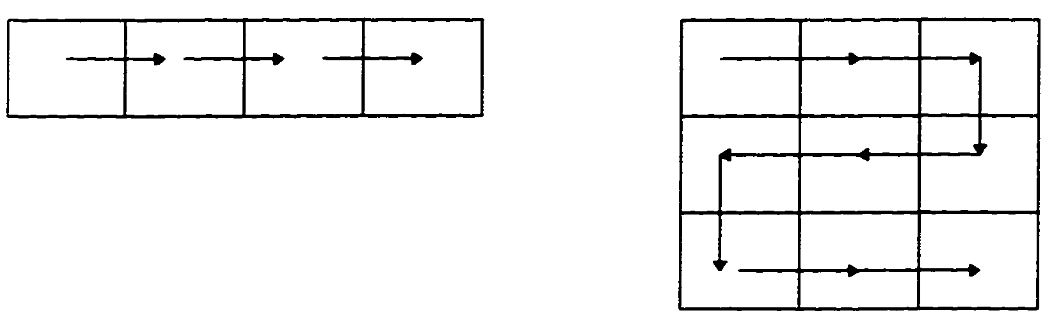

Figure 6-2: Sample Flow Shop Layouts

6.1.2. Example of Arc Crossing Interchange

Using the Tip Node Technique for arranging departments given the following flow matrix, Table 6-1, which was constructed from the data as detailed in Chapter 5, the layout below is generated.

Table 6-1: Flow Matrix for Example

Dept	A	B	C	D	E	F
A		1				
B	1		1			
C		1		1		
D			1		1	
E				1		1
F					1	

The arcs in the figure below represent an overlay of the cut tree.

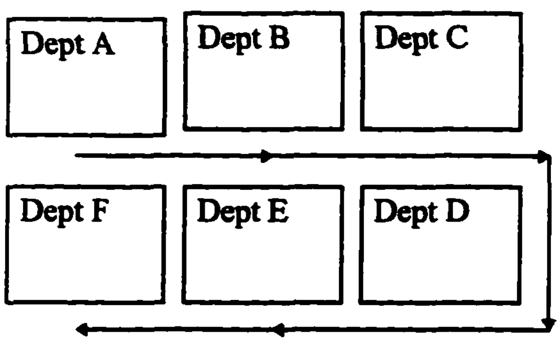

Figure 6-3: Example Layout

If the demand patterns change such that the following matrix now represents the product flow, a simulation experiment of the model with the current demand scenario would recommend that departments C and D be interchanged.

Table 6-2: Example Flow Matrix with Drift

Dept	A	B	C	D	E	F
A		1				
B	1			1		
C				1	1	
D		1	1			
E			1			1
F					1	

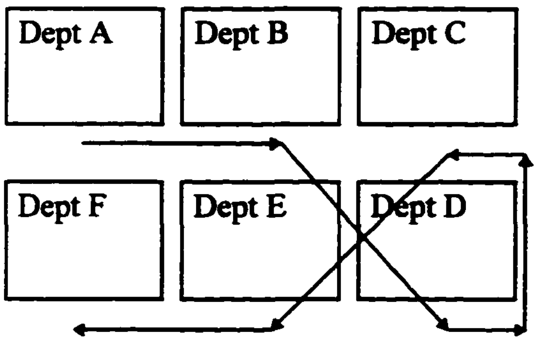

Figure 6-4: Example Layout Showing Drift

By switching departments C and D, the flow is clearly returned to an optimal state.

6.1.3. Example of Cut Tree Node Neighbor Interchanges

Consider the flow matrix in Table and the current departmental arrangement of Figure 6-5. The arrows represent the cut tree arcs drawn between the respective department's material handling location.

Table 6-3: Example Flow Matrix

Dept	A	B	C	D	E	F
A		6				
B	6		6			
C		6		3	2	1
D			3			
E			2			
F			1			

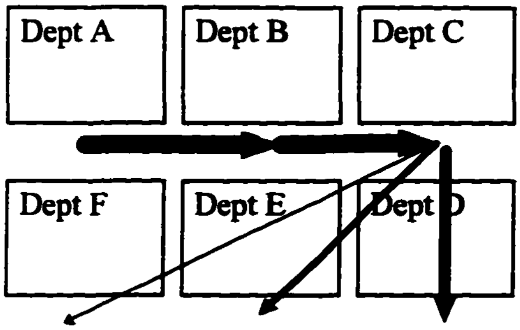

Figure 6-5: Example Layout

If the flow characteristics where to change to that indicated in the flow matrix of Table 6-4 and represented in Figure 6-6, the interchange procedures identifies the

Table 6-4: Flow Matrix with Demand Drift

Dept	A	B	C	D	E	F
A		6				
B	6		6			
C		6		1	2	3
D			1			
E			2			
F			3			

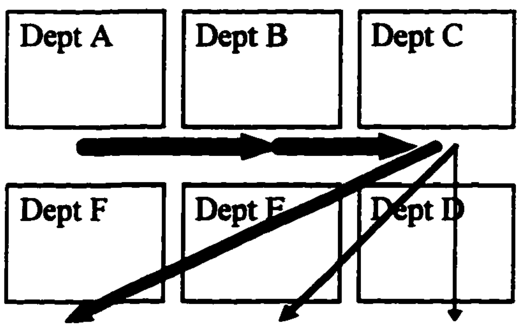

Figure 6-6: Layout Showing Demand Drift

interchange of departments F and D which, given a constant aisle structure, returns the layout to an optimal state.

6.1.4. Aisle Width Determination

Aisles consume a significant quantity of space in a plant. Sule (1988) suggests that aisles account for 20-40% of the area in a production facility. By only allowing flow on an aisle in one direction, the area required for aisles can be reduced, potentially, by half. Basgall (1988) found that when single-directional aisles with looping and spurs to be more cost effective than bi-directional flow for AGV systems, particularly when the cost of floor space is considered and when the number of vehicles increases. This makes an additional 10-20% of the floor space available for productive uses. For each layout developed, the methodology as implemented presents the area consumed in aisles as well as its value. The value of an available unit area is specified by the user. The user can then reduce the width of the aisles and specify a single direction of flow. Executing a simulation experiment will then predict the impact on the material handling system cost, WIP, and flow time.

6.1.5. Layout Considering Perimeter Aisles

The existing techniques which do utilize the cut tree as a basis for determining aisles, do not provide examples of restricting those aisles. Most, to be fair, are focused are minimizing the aisle structure. In practice, however, there are key aisles which are tied to key features of the structural design of the facility.

Another feature that is very common in industry is the utilization of perimeter aisles. That is, many factories line the perimeter with aisles. Certainly, this is required for guaranteed access to all portions of a department. For example, an assembly line next to a wall must be longer if only one side is accessible since the other side cannot be used for storage of material and access to the product by workers.

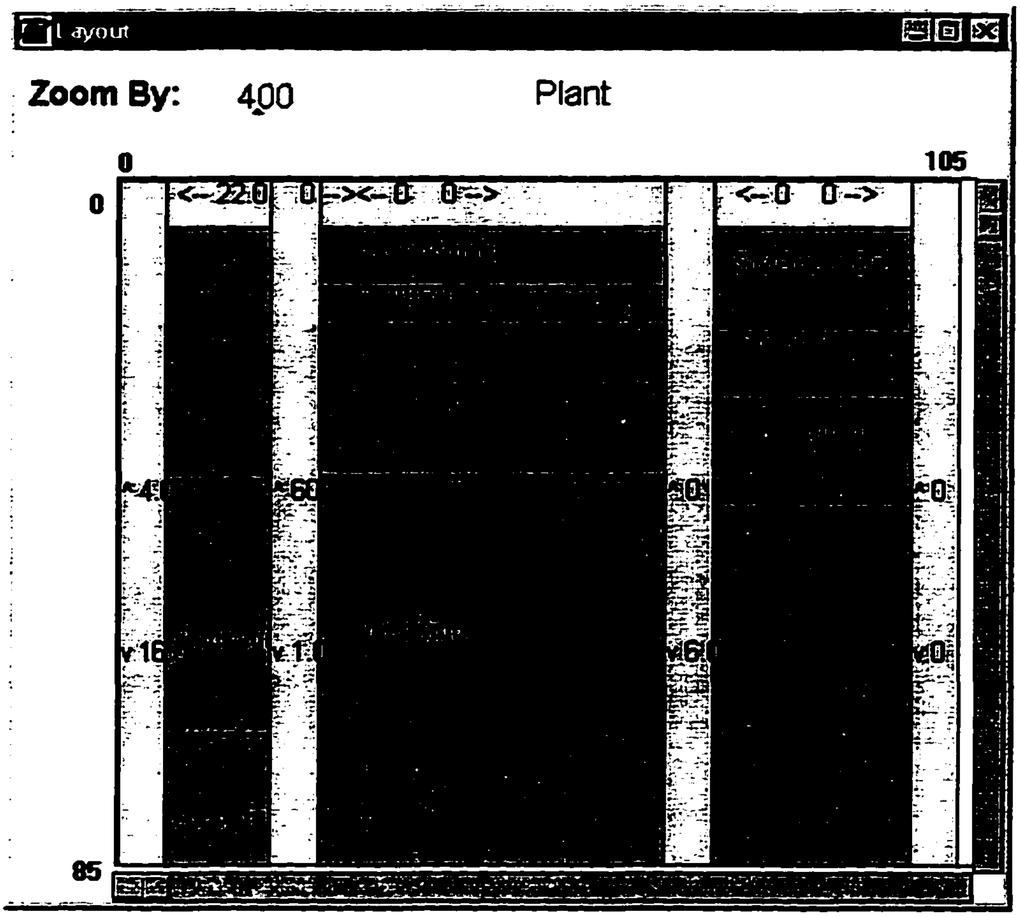

Figure 6-7: Layout with Perimeter Aisles

The methodology developed here allows optional specification of perimeter aisles. Figure 6-7 shows an example layout with perimeter aisles on three sides of the plant. The numbers on the aisles are the flow in each direction along those aisles based on the Floyd's algorithm material routing paths and the flow matrix calculated from product demand, the bill of materials, and the routings information.

6.1.6. Sample Session Using the Layout Analysis and Improvement Workbench

This section provides an example layout analysis session with the

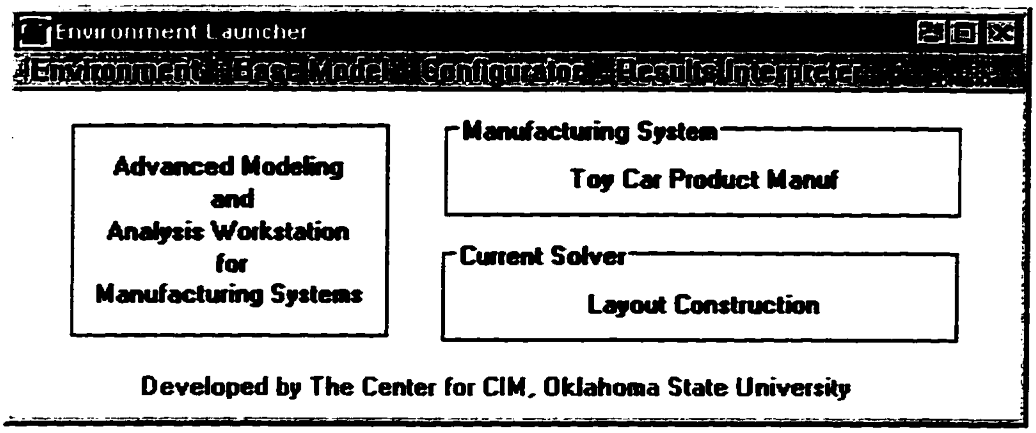

Figure 6-8: Environment Interface

methodology implementation.

The first step is to load the description of the system and its operating characteristics. The problem presented is the manufacture of a toy car. The data presented here must be available and is used by the simulation, but it is not the core part of the layout analysis and improvement process. Much of the interface and data structure development which is used for the data specified in the first portion of this section was developed along with other members of the research team at the Center for Computer Integrated Manufacturing at Oklahoma State University. The presentation order is the most usual for specification of data from scratch.

Consistency of navigation tools was incorporated to the extent possible. In general the following is true. The "Add" button is used to add a new item. The

"Delete" button deletes the selected item. The "Update" button saves the changes made to fields in a particular interface screen. The "Cancel" button cancels the changes to the values in fields and returns those values to the previously saved values. The "Close" button closes the current interface. This button will automatically update any changed fields.

The bill of materials (BOM) interface for the problem is shown in Figure 6-9. The finished goods product is highlighted so that its single level explosion is displayed. The entire bill of materials structure is shown in Figure 6-10. Each "leaf" (i.e., lowest level, least complex) item is specified as purchased or manufactured. The BOM Leaf Parts Information Interface allows the user to specify this information (see Figure 6-11). Note that the standard cost of an item is specified. This is used in calculation of WIP values by the solver. In Figure 6-10, the purchased items are shown with a long-dash line style. The raw material used for manufactured leaf items are denoted with a short-dash line style.

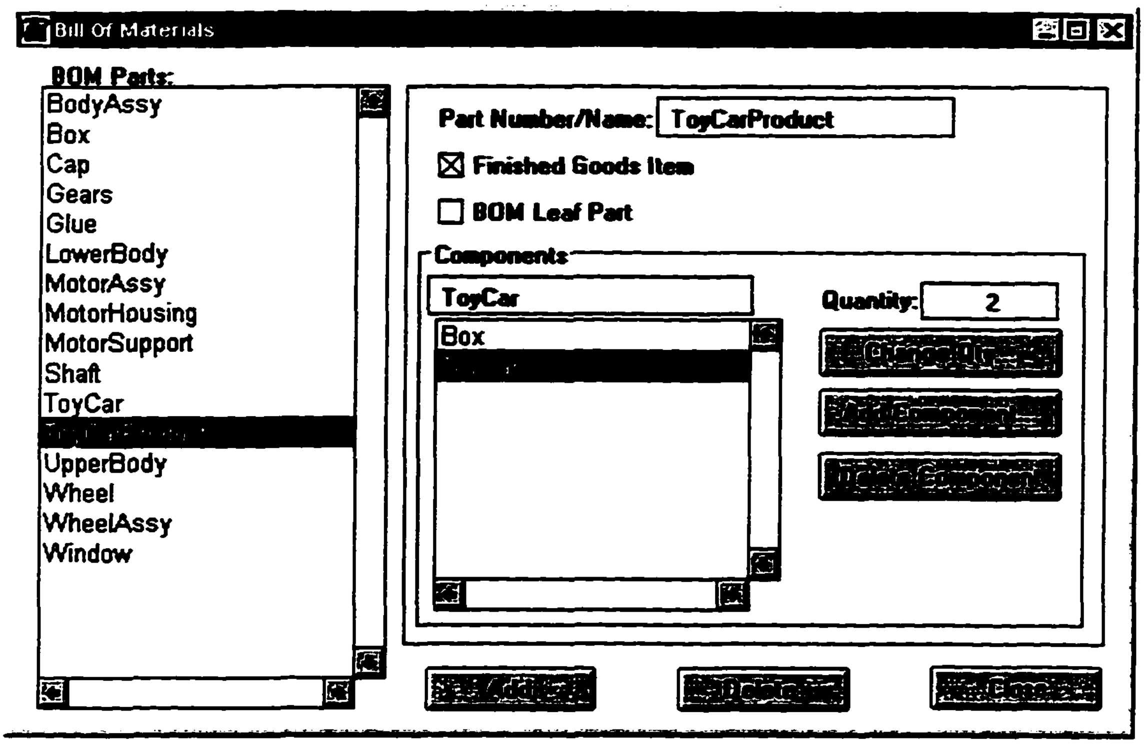

Figure 6-9: Bill Of Materials Interface

After the BOM structure is specified, the user specifies physical and control information regarding the plant and its components organization. This includes departmental organizations and all the workcenters in those departments. Since specification of the layout parameters for each department and the plant material handlers are key to the layout analysis and improvement process, detailed discussion was included in the body of the text. For this example, one processing station is located in each department. In essence, a department is modeled as a single processor.

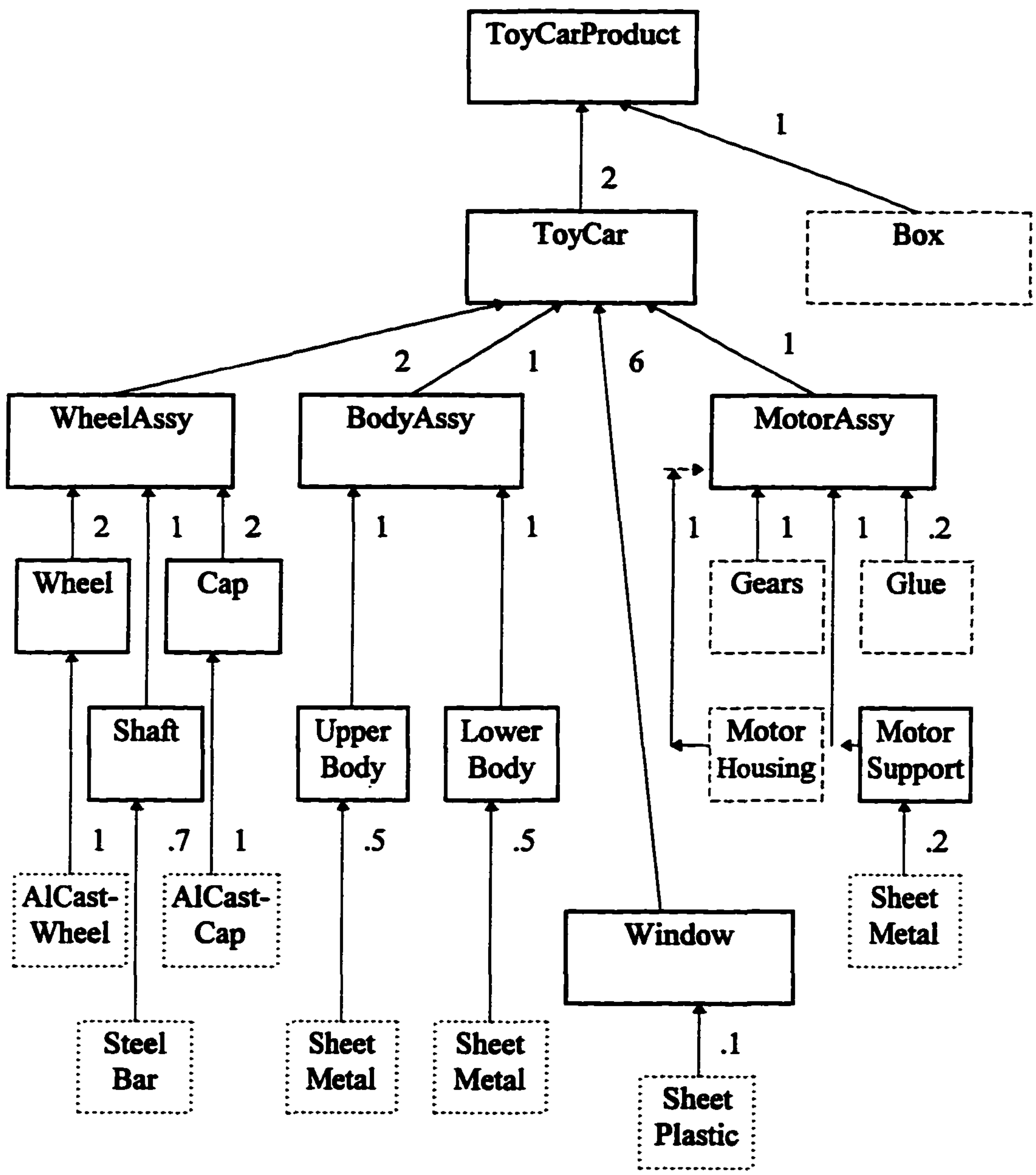

Figure 6-10: Bill of Materials Structure

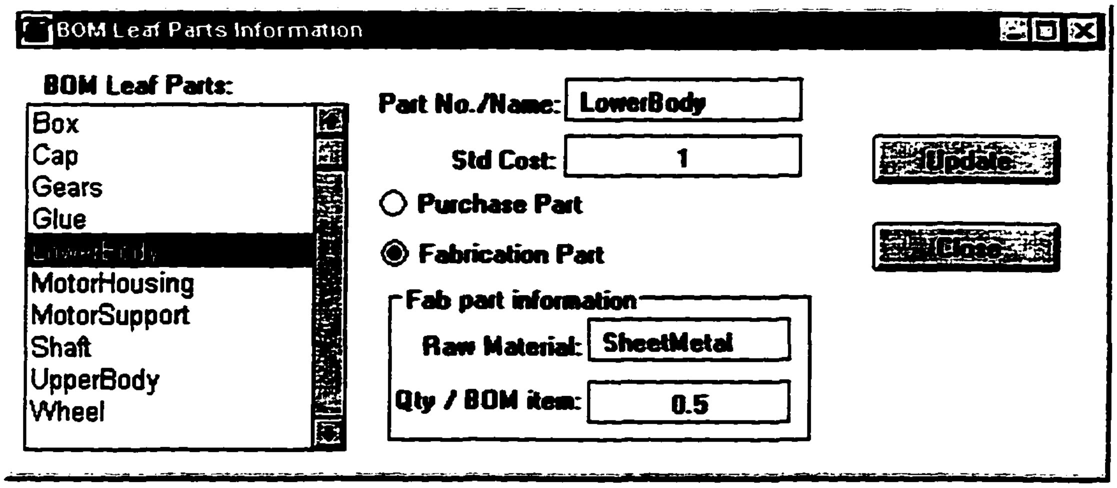

Figure 6-11: BOM Leaf Parts Interface

The Plant and each of its component have their own controllers. The program is coded such that at most event points and decision points, the logic used to make a decision and/or used to proceed with processing is "pluggable". That is, a method (i.e., simple subroutine) can be developed which implements a particular logic. By placing this method in the right location in the code, it immediately becomes available for the user to select and utilize in the model. Figure 6-12 shows a sample of this interface. For a given object, the "Function Controls" is a categorization of the types of control and decisions points available for the particular object. The "Decisions List" is the actual decision points for that object for the selected function. The user specifies the "Logic Option" to use when the control point is encountered during an execution model experiment. Figure 6-13 shows the same interface with a different function highlighted. Note that in this example, there are two logic options available to the user.

Similarly, each department (see Figure 6-14) and each workstation and assembly station (see Figure 6-15) have a control information which must be specified. In this example, the default logic options were selected unless otherwise indicated.

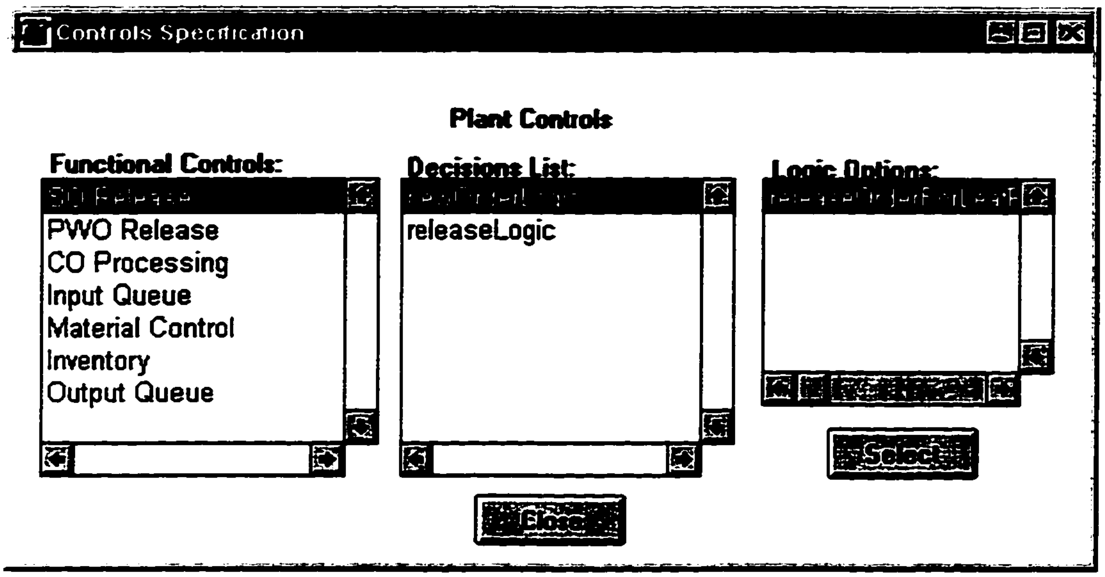

Figure 6-12: Plant Controls Interface

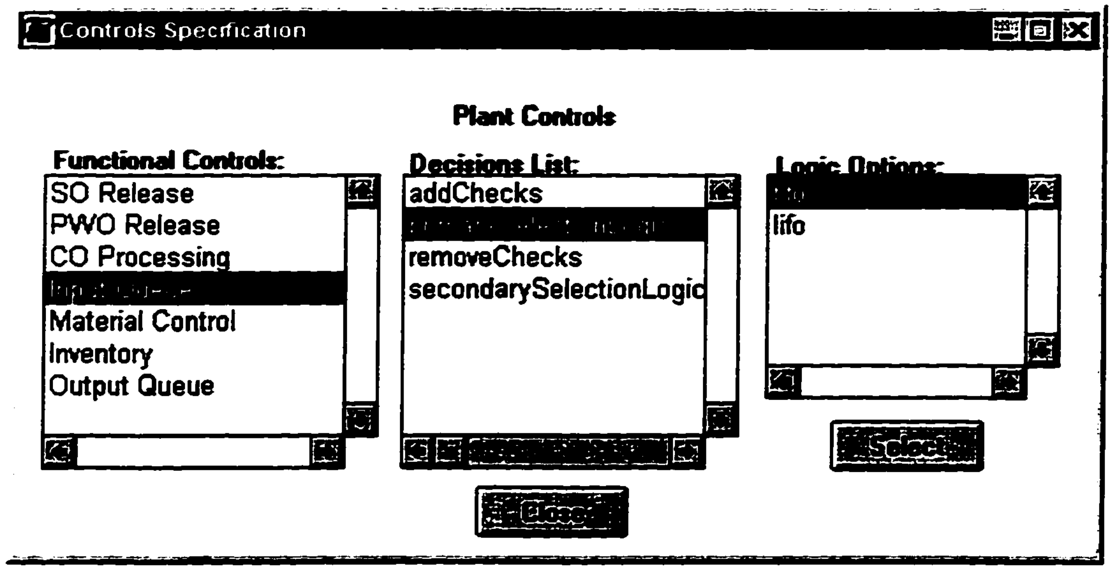

Figure 6-13: Plant Controls Interface 2

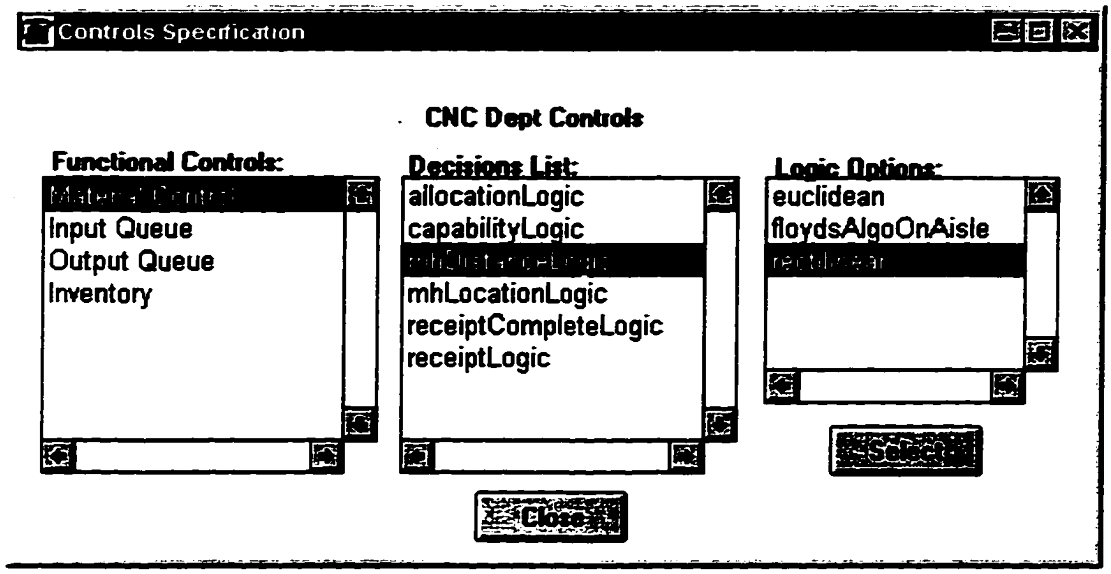

Figure 6-14: Departmental Controls Interface

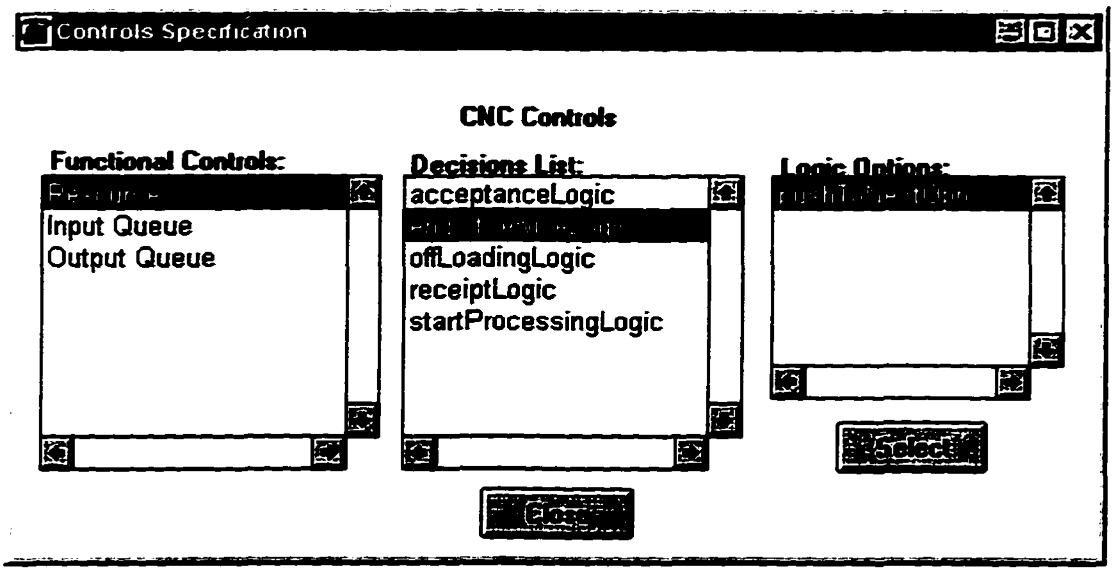

Figure 6-15: Work Station Controls Interface

The next step in the process is the specification of the purchased material informational properties. This includes the lead time distribution for each item, the inventory control method for each item, and the storage location for each item. The details of a sample item are displayed in Figure 6-16. When the user selects the

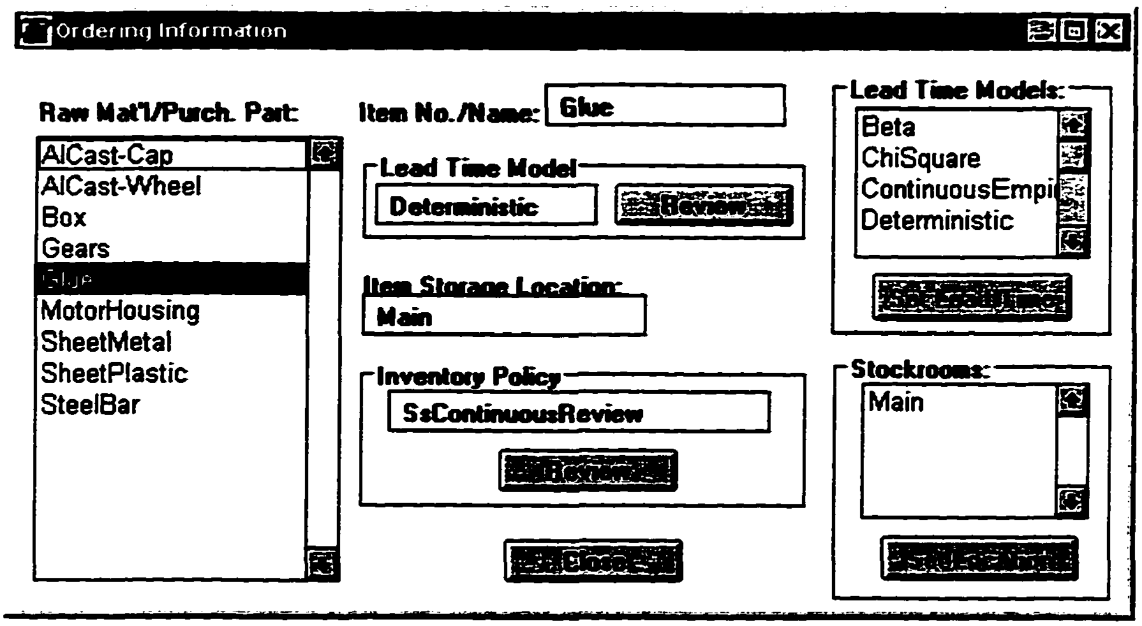

Figure 6-16: Purchased Material Interface

"Review" button, the parameters of the specified probability distribution or inventory policy are displayed and may be changed. For this problem, the (s,S) policy is specified as (500,1000) and all lead time distributions are Deterministic(48).

At the other end of the process, information must be supplied regarding each finished goods item. This process is very similar to the Purchased Material Interface with the exception that instead of a lead time distribution, a distribution is specified to model the time between demands. A sample of the Finished Goods Interface is presented as Figure 6-17. For this example, the ToyCarProduct demand interarrival time is modeled with Triangular(0.5,1.0,1.5). The (s,S) inventory policy parameters are set at (10,15).

Product routings are specified with the Routings Interface, a sample of the interface screen is show as Figure 6-18. The details of all routings are listed in Table 6-5.

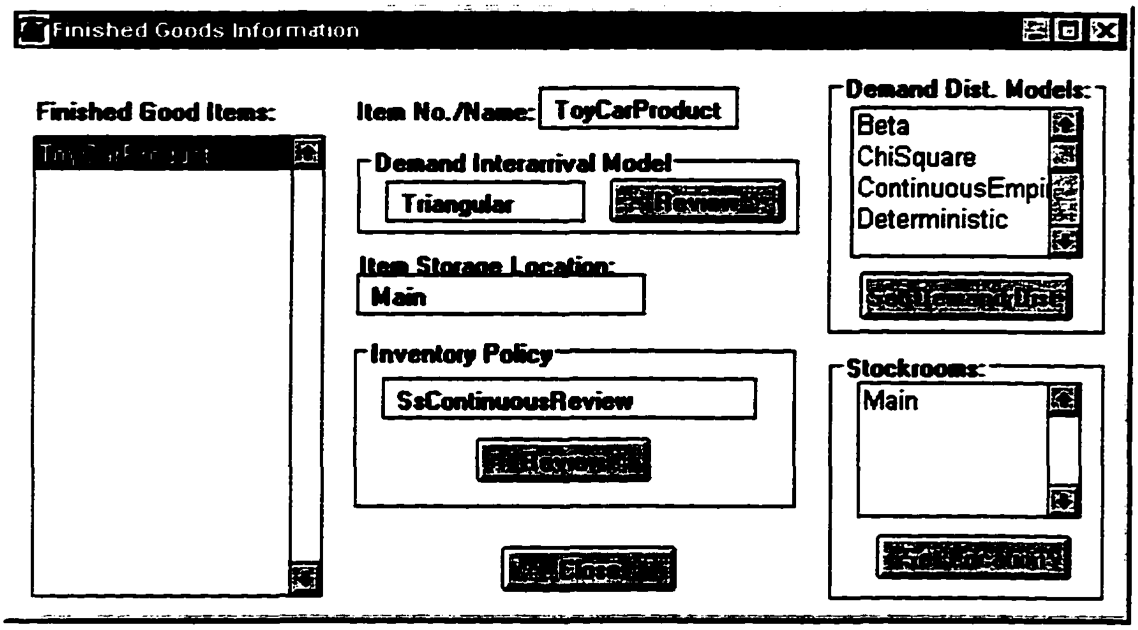

Figure 6-17: Finished Goods Interface

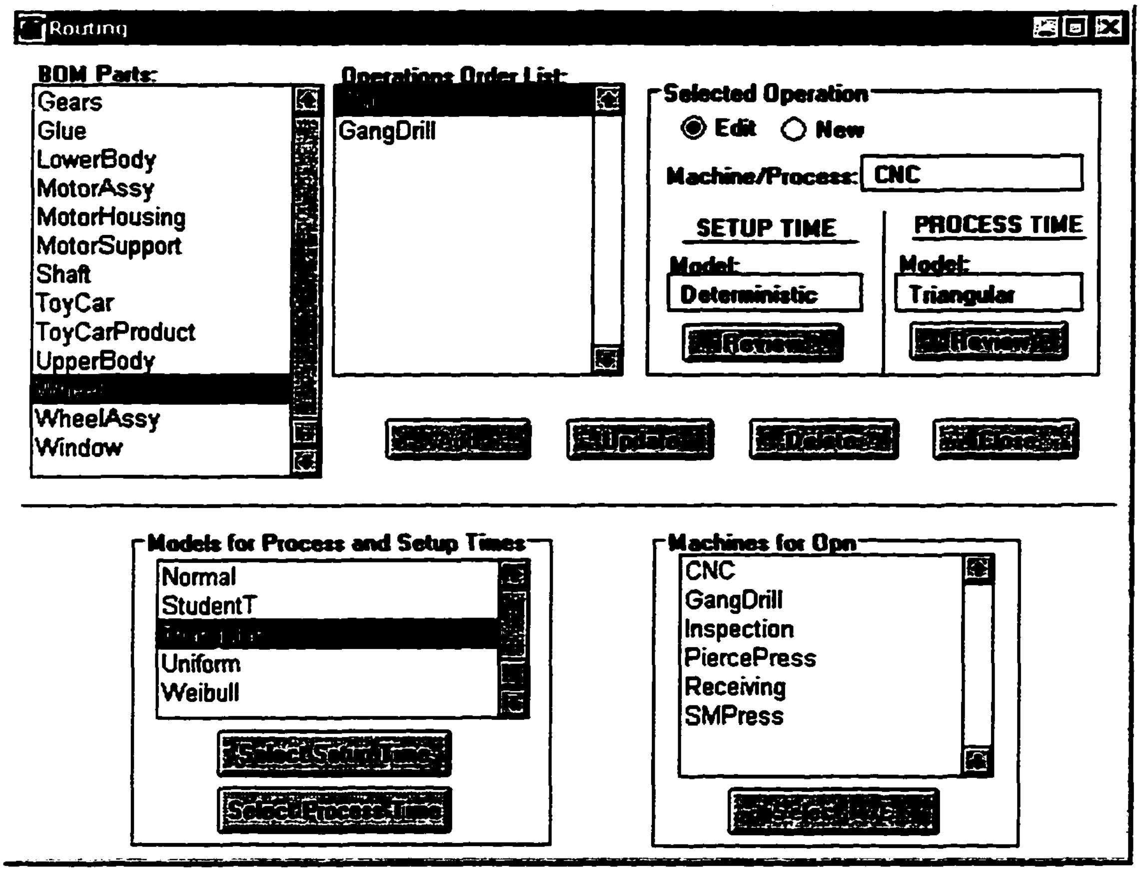

Figure 6-18: Routing Interface

Table 6-5: Toy Car Problem Routings

Part	Opn List	Setup Time Model	Process Time Model
BodyAssy	Snapper	Deterministic(0)	Triangular(0.1,0.2,0.3)
Cap	CNC	Deterministic(0)	Triangular(0.05,0.1,0.15)
	GangDrill	Deterministic(0)	Triangular(0.1,0.15,0.2)
LowerBody	SMPress	Deterministic(0)	Triangular(0.05,0.1,0.15)
MotorAssy	Assy-Motor	Deterministic(0)	Triangular(0.2,0.3,0.4)
MotorSupport	SMPress	Deterministic(0)	Triangular(0.05,0.1,0.15)
Shaft	CNC	Deterministic(0)	Triangular(0.05,0.1,0.15)
ToyCar	Assy-Final	Deterministic(0)	Triagular(0.3,0.35,0.4)
ToyCarProduct	Packaging	Deterministic(0)	Triangular(0.05,0.1,0.15)
	Inspection	Deterministic(0)	Deterministic(0.1)
UpperBody	SMPress	Deterministic(0)	Triangular(0.05,0.1,0.15)
Wheel	CNC	Deterministic(0)	Triangular(0.1,0.2,0.25)
	GangDrill	Deterministic(0)	Triangular(0.1,0.15,0.2)
WheelAssy	Assy-Wheel	Deterministic(0)	Triangular(0.2,0.3,0.4)
Window	PiercePress	Deterministic(0)	Deterministic(0.005)

Upto this point the majority of the data structures and interfaces presented in this section were developed by the research team at the Center for Computer Integrated Manufacturing at Oklahoma State University where the author was an active member from 1990 through 1994. The majority of the following extensions built on that environment were developed by the author as part of the this work. Access to the interfaces for specification of this data is granted through the main

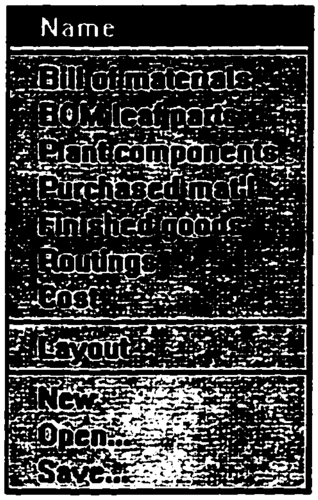

Figure 6-19: Base Model Menu

"Environment Interface". Figure 6-8 shows this interface and Figure 6-19 shows the "Base Model" menu bar menu.

As part of specifying the characteristics of the plant being analyzed, the user must indicate the restrictions on the area and shape of each department. For this example, each department is allowed flexibility in both location and shape with the restrictions show in Table 6-6.

Table 6-6: Departmental Requirements

Department	*Target Area*	*Min Area*	*Min Side*
Assy-Final	320	290	8
Assy-Motor	320	290	10
Assy-Wheel	320	290	10
CNC	480	430	10
GangDrill	200	180	6
Inspection	400	360	10
Packaging	400	360	10
PiercePress	320	290	10
Receiving	2400	2160	20
SMPress	320	290	10
Snapper	200	180	10

To begin the arrangement process, the analyst then selects "Layout" from the Base Model menu on the Environment Interface menu bar. The "Layout Analysis and Improvement Workstation" window is displayed (see Figure 6-20).

As displayed in the figure, the analyst has previously simulated and saved results on the current layout. For this session, the analyst desires to determine if there are any potentially beneficial re-arrangements of the facility.

From this interface the user has access to the layout generation parameters via the "Setup" button and (see Figure 6-20), the simulation tool (see Figure 5-17).

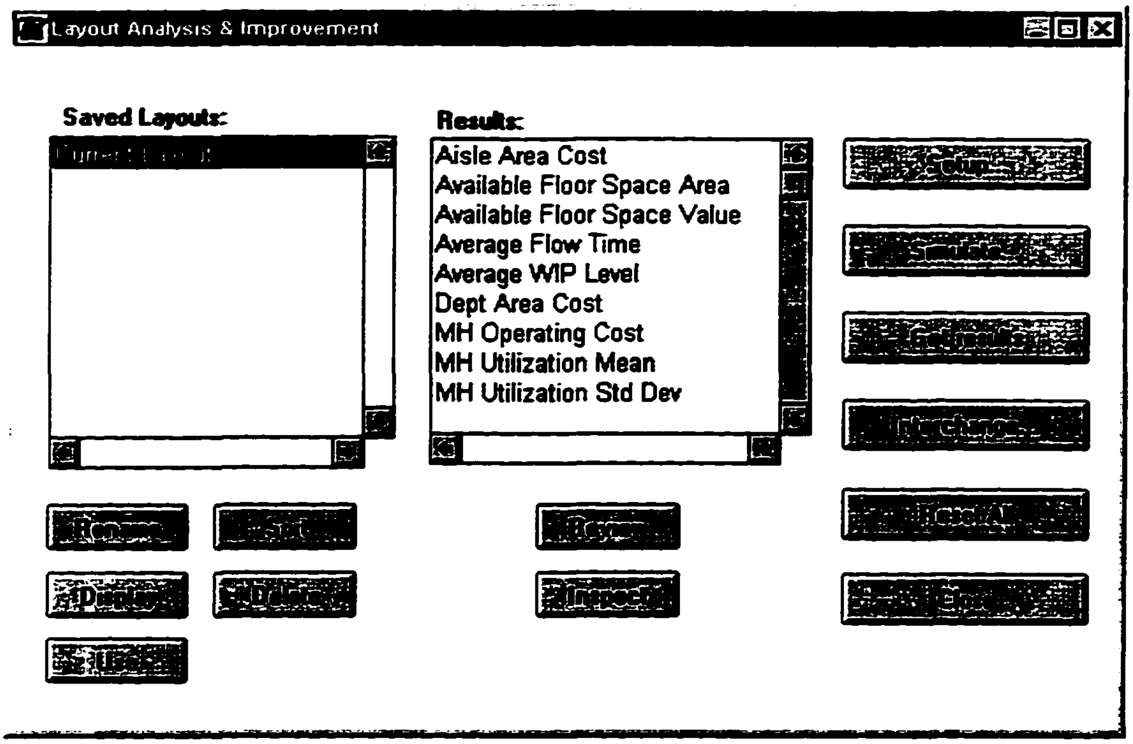

Figure 6-20: Layout Analysis and Improvement Interface

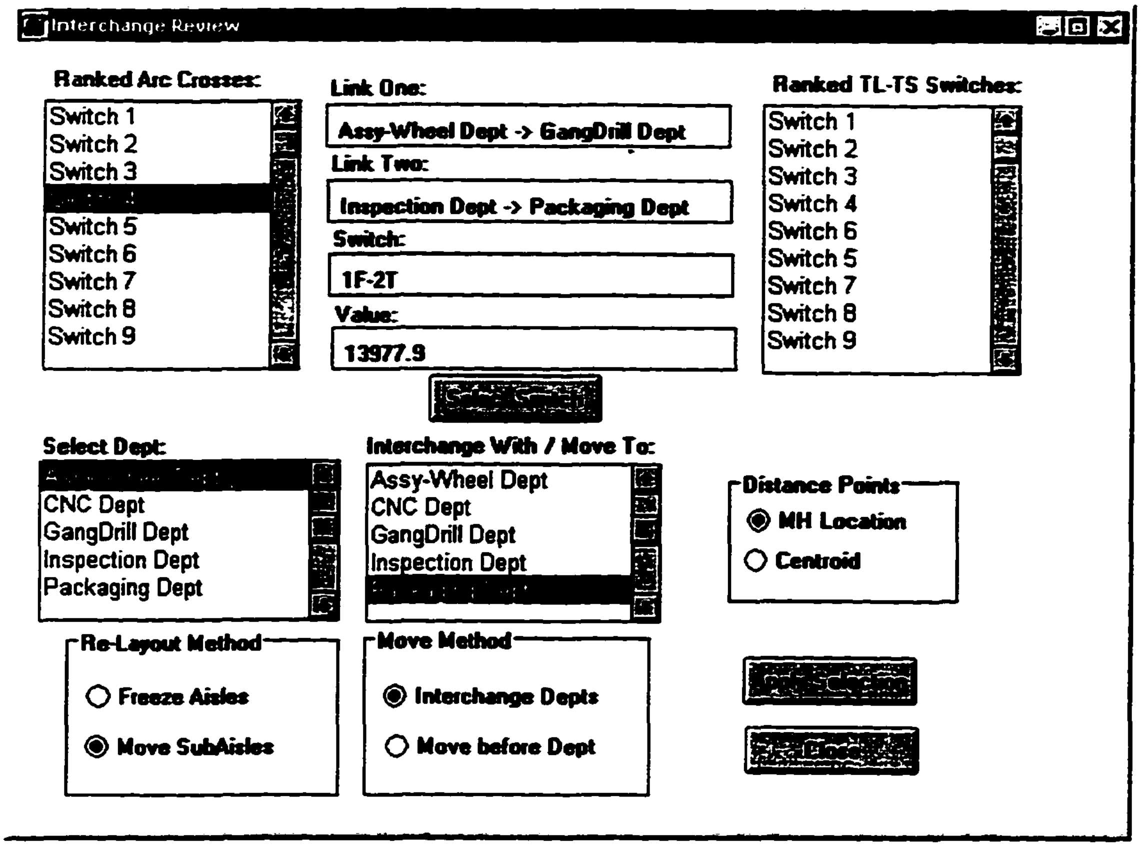

Figure 6-21: Interchange Interface

The "Get Results" button is used to pull the results from the last simulation into this layout analysis tool for storage and comparison. Having completed a simulation of the current situation as a baseline, the analyst then selects "Interchange" to display the Interchange Interface. This interface as displayed in figure presents potential improving departmental interchanges. For this session the crossed cut tree arc switches were considered. Switch 1 and Switch 3 involved relocating the Receiving Department. Because of its size, such an interchange would necessitate practically a complete re-arrangement of the whole facility. Switch 2 and Switch 4 involve the same cut tree arcs, but switch different end points. Because more complex interaction was involved, the analyst decides to try Switch 4 first. This switch is highlighted in Figure 6-21.

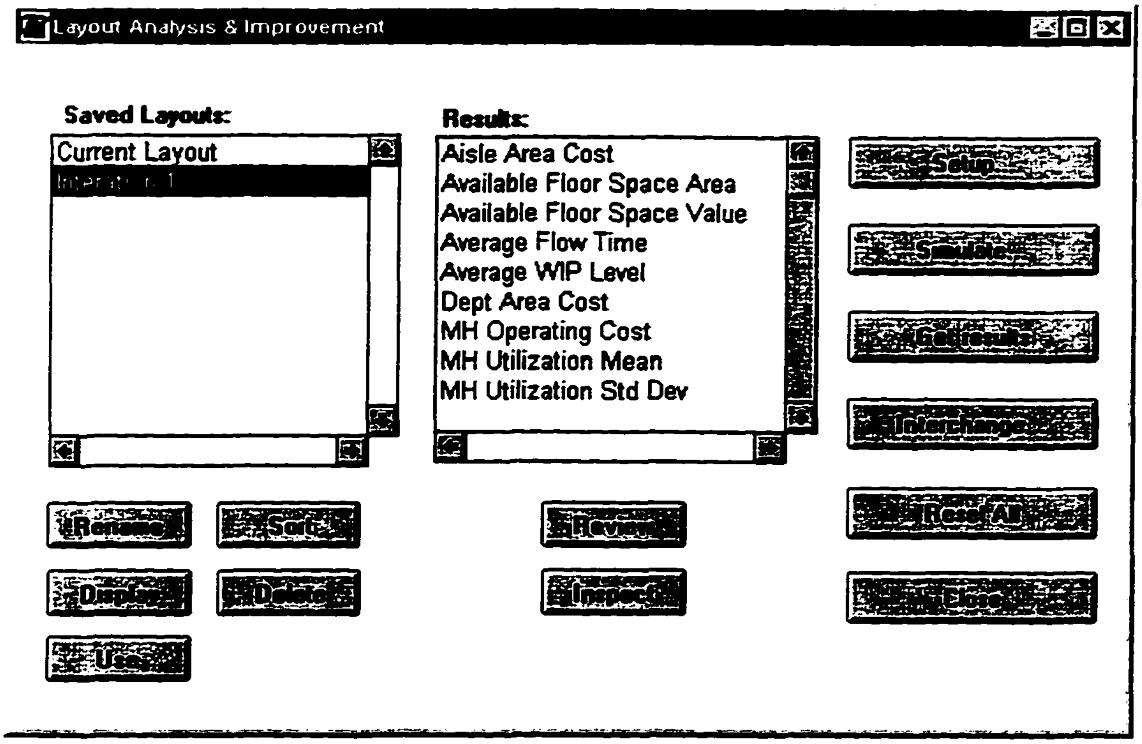

Figure 6-22: Layout Analysis with Two Saved Layouts

The analyst clicks the "Apply Selection" button to make the interchange in the model. After closing this window, the analyst clicks the "Simulate" button and executes a simulation experiment. When the simulation is complete, the "Get Results" button is selected. The interface then displays the additional saved layout (see Figure 6-22).

The user is able to "Review" the values of the saved performance measures. A set of key performance measures from the simulation are saved for ease of comparison and analysis. The user may "Sort" the saved layouts based on a selected criteria. The user may "Display" a saved layout. The user may "Use" a layout; that is, make a saved layout the active layout in the model.

For the situation presented, the analyst is interested in material handling system operating cost and WIP levels, in particular. Table 6-7 compares these metrics for the two layouts. The user may continue alternative layouts using the recommended interchanges or by reviewing the visual tools offered and testing interchanges and moves as desired.

Table 6-7: Performance Critieria Comparison

Metric	*Current Layout*	*Layout after One Iteration*
WIP Level Average	1039.36	519.32
MHS Operating Cost Average (annualized)	$54,991.50	$53,884.20

By viewing the layouts with the cut tree overlay tools, the analyst, the user can see that they indicate that there is potential for an improved solution. Figure shows the current layout and figure shows the layout after the interchange. The overlay displayed uses the departmental material handling locations for node points.

Simulation also affords the opportunity to determine situations where a particular layout may be better than another with some probability. In traditional techniques, expected values are used and a layout has a static evaluation. In simulation, time elements and decision making can be modeled stochastically. Therefore, whether or not one layout is superior can vary based on actual realizations. As an example, the above model was changed such that the processing times were modeled with exponential distributions rather than triangular distributions. Multiple simulation runs produced the results in Table 6-8 and Table 6-9.

Table 6-8: Simulation Results on WIP Level

Layout	*Run 1*	*Run 2*	*Run 3*	*Average*
Current	528.529	528.267	1058.29	705.029
After Interchange	1055.38	531.697	532.367	706.481

Table 6-9: Simulation Results on MH Operating Cost

Layout	*Run 1*	*Run 2*	*Run 3*	*Average*
Current	54,522	54,671	54,548	54,580
After Interchange	53,495	53,669	53,673	53,612

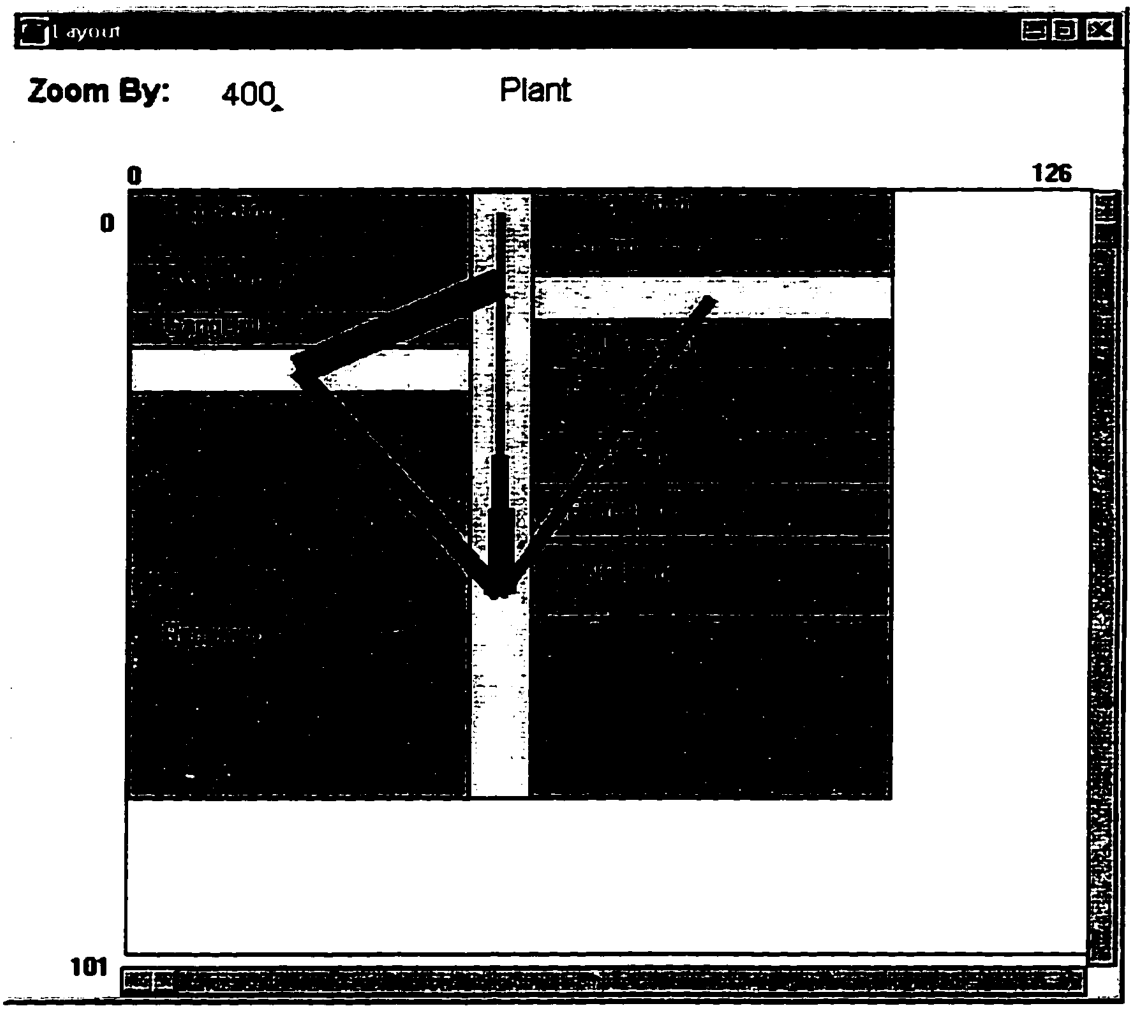

Figure 6-23: Sample Session Current Layout

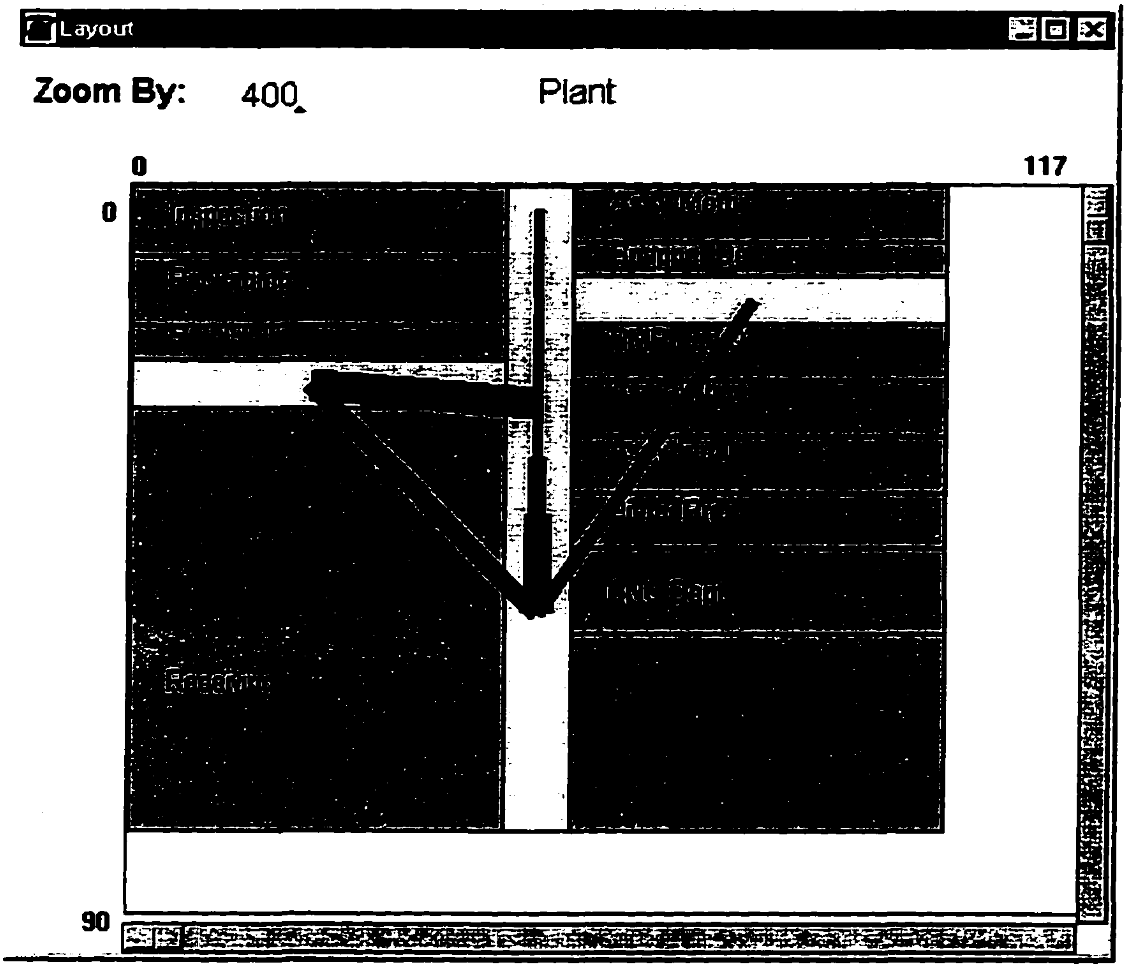

Figure 6-24: Sample Session Improved Layout

7. SUMMARY OF CONTRIBUTIONS TO FACTORY DESIGN PRACTICE

This work has made three major contributions to the research presented in the plant layout literature. These are

1) Development of a new procedure for arranging departments within a plant which locates departments around an aisle structure allowing restrictions on department location and shape.
2) Integration of a layout procedure with simulation creating the ability to evaluate multiple, stochastic system performance measures and allowing simultaneous engineering of the production system design.
3) Generation of a Layout Analysis and Improvement Workbench to assist the analyst in the departmental arrangement and/or re-arrangement process.

A technique, CT-FAST, for arranging departments in a plant was developed based on the cut tree calculated from the bill of materials, routings, and product demand. This technique places departments around a logical aisle structure. The following capabilities are present in the technique: handles unequally, but rectangularly shaped departments; handles pre-specified, fixed location departments, allows departmental areas to be fixed or to be specified as a range, allows departmental shapes to be fixed or flexible, allows minimum dimensions to be specified for departments, allows aisle locations to be fixed or to be specified with a range, allows aisles to be specified on the perimeter of the plant, requires the width of the aisles be specified.

Traditionally plant layout techniques have provided layout alternatives based on long term estimated average values. Computer simulation has been used to more thoroughly evaluate layouts, but usually in a trial and error design procedure. The implementation developed as a part of this work, allows the user to alter the arrangement of departments, and/or the aisle locations and properties without explicit changes to the simulation model. Another feature of this integration is that it allows the co-engineering of the production system design. The layout can be developed based on rough estimates of material flow. As more detailed and accurate information is available, it can be included. The same is true of the material handling system. A leading author in the plant layout literature, Meller and Gau (1996-2), called for such a concurrent engineering tool. Usually, the material handling system design problem is not addressed until after a layout is determined. The implementation of this effort allows various material handling systems to be compared with a constant layout as well as various layouts to be evaluated considering the same material handling system. The stochastic nature of simulation allows the analyst to determine the risk of selecting a sub-optimal layout. That is, when considering two layouts, the best layout with respect to a particular performance measure may not be guaranteed because future demand and actual processing times cannot be predicted precisely. The interface to this integrated tool is specifically targeted at production system evaluation for discrete part manufacturing operations. The interfaces are modeled after commercially available manufacturing execution systems as opposed to a generic simulation modeling language. This brings the power of computer simulation closer to an analyst whose expertise is on the system being modeled rather than on the simulation solver.

The Layout Analysis and Improvement Workbench organizes the layout analyst's facility design process. From the Workbench window, the user can setup the layout parameters, execute a simulation experiment, review saved layouts, and alter layouts. In addition to the dimensions of the layout, key metrics are stored and layouts can be ranked by an available metric. The "Interchange" module presents the user with recommended interchanges as well as a means for executing a recommended or user-specified interchange. The Workbench including the interchange module is useful for analyzing re-layout opportunities. As costs and demand patterns change over time, potential improvement opportunities are identified.

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