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Plant Layout Design System using a Hybrid Approach with a Constraint-Directed Search and a Mathematical Optimization Technique*

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A plant layout design system is proposed using a hybrid approach with a constraint-directed search procedure and a mathematical optimization technique. In layout design, a plant must be arranged to satisfy spatial constraints imposed by its components. In our approach, the whole space of a plant building is divided into finite compartments with a modular size in order to separate the description of the layout into the combinational part and the dimensional part. According to this, the approach consists of two steps. In the first step, a constraint-directed search procedure is applied for fixing the combinational relations among plant components so as to satisfy the spatial layout conditions. In the second step, an optimization technique is applied for determining the actual dimensions of compartments so as to minimize the size of a plant building taking the size of components into consideration. In the optimization, mixed-integer programming and sequential linear programming are combined and the mathematical model is formulated automatically from the result of the first step. The system using this hybrid approach has been applied to the design of a nuclear power plant in order to check its validity and effectiveness.

Key Words: Design Engineering, Layout Design, Optimal Design, Mathematical Optimization, Constraint-Directed Search, Plant Layout

1. Introduction

In the design process of power plants, the layout design is a very important process, in which the positions of facilities and equipment are arranged in a plant building. Computer applications have been expected to be indispensable tools for layout design since the early days, and some computer systems have been developed using mathematical optimization techniques or artificial intelligence techniques(1)-(4). However, as for the applications of optimization techniques(1), it is difficult to represent various kinds of spatial conditions as mathematical formulas, and their applications were limited to simple layout problems. In the expert systems(2)-(4), symbolic programming techniques and heuristics are introduced. However, most of them were applied to planar layout problems. Moreover, the number of facilities and amount of equipment are small in comparison with practical applications in power plants.

The characteristics of the layout design of power plants can be summarized as follows: (1) the layout problem is spatial, (2) the sizes of the plant components are different from each other, and (3) the components are laid out so as to fit into a plant building. The methodologies of the aforementioned approaches are not suitable for this kind of plant layout design problem. Therefore, we have proposed an approach for the preliminary layout design problem of power plants by using a constraint-directed search technique and the representation method of layout space with the compartments(5). The system based on the approach(6) was successfully applied to some layout design problems of nuclear power plants.

In this paper, we present a hybrid approach which is developed by enhancing the above approach(5),(6) so as to support the wider range of the layout design problems. In the new approach, the layout space, i.e., the whole space of a plant building, is represented as

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a set of the finite number of compartments with an approximate unit size⁽⁵⁾. Based on this, in the first step of the approach the spatial relations among plant components are fixed with a constraint-directed search algorithm⁽⁵⁾·⁽⁶⁾, and in the second step the exact sizes and positions of respective compartments are determined with a mathematical optimization algorithm (Fig. 1).

Finally, the developed approach is applied to the design of a nuclear power plant in order to check its validity and effectiveness.

2. Plant Layout Design Problem and Its Characteristics

2.1 Positional relations between plant components

In the process of plant layout design, we must determine the positions of plant components, which are the rooms for equipment such as pumps, heat exchangers and tanks. In the layout, no overlap of any type between components is permitted. In order to produce such a layout, we must mathematically check the exact positions after fixing their spatial relations as shown below:

Figure 2 gives example cases for this situation. In the figure, the shapes of components are assumed to be rectangles and they are laid out in the regions, $(x_{i-}, y_{i-})-(x_{i+}, y_{i+})$, $(i=A, B)$. In case I, if component A can be moved only in the direction of the x axis, the overlap between components A and B can be checked with an inequality, $x_{A+} \leq x_{B-}$. On the other hand, in case II, if component A can be moved only in the direction of the x axis, it is not necessary to check the overlap with any inequalities. However, if component A can be moved in any direction, we cannot check the overlap only with the above inequality. We must check the overlap combining with the combinational conditions such as "if component A is located out in the upper area of component B". Namely, we must fix the combinational relations on the positions of components before exactly checking their overlap with mathematical formulas.

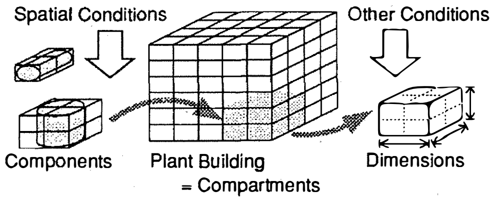
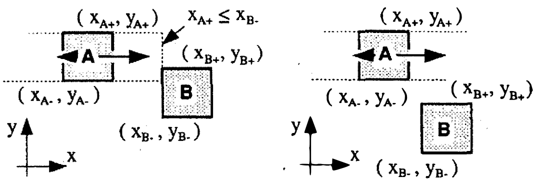


Fig. 1 The concept of the approach



Case: I Case: II

Fig. 2 Positional relations between components

Table 1 Examples of components and their sizes

Component	Dimensions [W × D × H in meters]	Compartments [W × D × H]
boric acid pump room	9.0 × 8.0 × 7.0	1 × 1 × 1
boric acid tank room A	7.6 × 6.5 × 14.5	1 × 1 × 2
charging pump room A	17.0 × 6.75 × 3.8	3 × 1 × 1
filter room	25.0 × 13.0 × 7.6	3 × 2 × 1
new fuel pit	18.4 × 11.0 × 12.5	3 × 1 × 2

In other terms, various conditions of layout design themselves can be defined as mathematical constraints and objective functions, but the definition of the problem includes some combinational conditions, as shown in Fig. 2. The mathematical procedures such as traditional optimization techniques are not adequate for the complicated layout problems.

In order to overcome the above situation, we separate the description of a layout into two parts: "topological relations among the components" and "exact positions of the components." Moreover, we must combine two procedures which are suitable for respective descriptions. Namely, we need a hybrid approach with a procedure for the combinational conditions of the topological layout and another procedure for the dimensional conditions of the exact layout.

2.2 Definition of the layout space with the compartments

The framework for separating the description of a layout is essential for the aforementioned hybrid approach. In the paper⁽⁵⁾, we have proposed "compartments" as a representation method of the layout space. Figure 1 illustrates this concept. With the concept, the layout space, i.e., the whole space of a plant building is decomposed into a set of a finite number of units, which are named the compartments, and the size of each component is also approximately defined with the number of compartments. Table 1 shows the exact size of some components and the corresponding number of compartments for the case of a nuclear power plant, which is mentioned in section 6. In the case of the table, a compartment approximately corresponds to a cube with 6~9 m edges.

By introducing the compartments, we separate the layout design process into the following two steps:

(1) **The preliminary step:** The process determining the topological relations among plant components by mapping them to the sets of compartments in order to fix the spatial combinations.

Table 2 Kinds and contents of layout conditions

Kinds of layout conditions		Contents of layout conditions	(1) Handling in the topological layout step	(2) Handling in the dimensional layout step
Conditions related to plant components	Size of each plant component	Required space must be assigned for each component.	The number of compartments is given for each component.	The minimum space size is given for each component.
	Spatial conditions imposed by plant operations	Component must be laid out so as to satisfy the spatial relations.	The constraints as shown in Table 3 must be satisfied.	The spatial relations fixed in the first step must be maintained.
	Conditions related to their pathways	For each component, a pathway with the necessary width must be assigned from the entrance to it.	The sequential line of compartments which corresponds to the pathway must be assigned.	The minimum sizes (widths) of the compartments corresponding to pathways are given.
Conditions related to plant building	Structural strength of plant building itself	A plant building must have enough strength to support machinery and itself under the given conditions.	Some cross sections of a plant building are assigned to structural walls.	The thicknesses of structural walls and floors are given.
Conditions related to plant cost	Cost of plant building itself	This is in proportion to the size of a plant building itself.	The total number of compartments is given as a condition.	The size of plant building is taken as an objective function to be minimized.
	Cost of piping	The total length of piping is closely related to a layout result, though it is directly related to the result of piping design.	The components connected by pipes should be laid out close to each other.	The spatial relations fixed in the first step must be maintained.

(2) **The embodiment step:** The process determining the exact positions and sizes of plant components, which correspond the actual sizes of the compartments, under the fixed topological relations.

2.3 Layout conditions of power plants

Before representing the approach, the conditions to be satisfied in the layout design of power plants are summarized. The conditions are classified into three groups in Table 2: the conditions related to plant components, the conditions related to a plant building, and the conditions related to plant cost. These conditions are also explained from the point of view of how they are dealt with in the respective layout processes mentioned in the previous subsection. Among the various conditions, the cost conditions are regarded as objective functions and the other conditions are regarded as constraints, in terms of traditional design optimization. However, it is difficult to describe them with mathematical formulas, and symbolic representation is suitable for describing them, especially in the preliminary step of the layout design process.

3. Outline of the Hybrid Approach

Figure 3 illustrates the outline of the hybrid approach based on the concept of the compartments. It is composed of the two procedures corresponding to the aforementioned separation of the layout design process.

In the first step, the topological relations among components are determined by applying a constraint-directed search procedure$^{(5),(6)}$, which is one of the artificial intelligence techniques. Namely, a plant building is defined as a set of compartments, and the positions of the components are determined as the combinations of such compartments so as to satisfy the spatial conditions shown in Table 2. The details are mentioned in section 4.

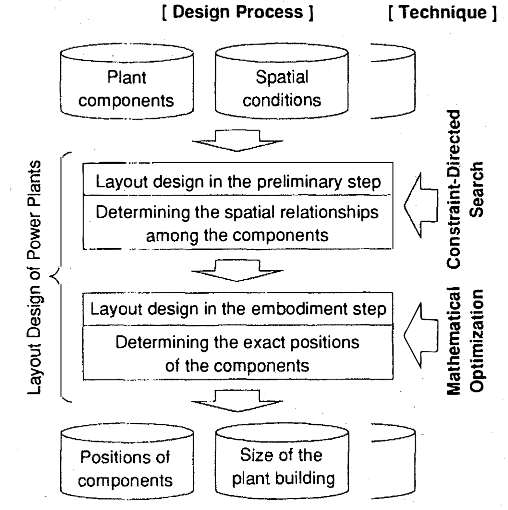


Fig. 3 Outline of the hybrid approach

In the second step, the exact positions of the components are determined so as to satisfy the other conditions under the topological combinations fixed in the first step. In this step, the combinational conditions have been fixed and most of the rest of the conditions can be defined with mathematical formulas. Then, the dimensional positions of components are determined by applying a mathematical optimization procedure. In the optimization, the size of a plant building is taken as an objective function to be minimized. The details of the formulation and procedures are described in section 5.

4. Fixing the Spatial Relations by a Constraint-Directed Search

In the first step of the approach, the topological relations among components are determined with a constraint-directed search algorithm under the representation of the layout space with the compartments(5),(6). The topological layout is constrained by the various conditions mentioned in Table 2, and they are declaratively represented as the constraints, as shown in Table 3. This kind of layout problem is treated as a search problem restricted by constraints. In our approach, the depth-first search algorithm is used as a fundamental framework. The obligatory constraints which are shown in Table 3 are evaluated for tree pruning, the suggestive constraints are used for evaluating the suitability of each feasible branch, and some heuristics are introduced. The outline of the algorithm is shown in Fig. 4. The topological layout as shown in Fig. 8 can be obtained with this algorithm.

Table 3 Examples of layout constraints

Classification	Examples
Obligatory constraint	
└Regional constraint	*A* is located higher than *B*. *A* is located on the highest floor.
└Combination constraint	*A* is located touching *B*. *A* is located in a different direction from *B*.
└Global constraint	*A* has a pathway to the entrance.
Suggestive constraint	
└Priority constraint	*A* is located close to *B*. *A* is located on a higher floor.

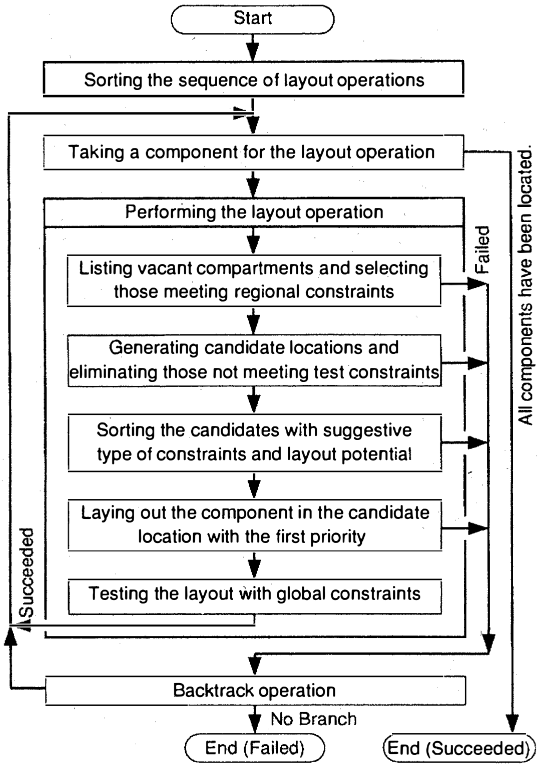


Fig. 4 Constraint-directed search algorithm

5. Determining the Exact Positions by an Optimization Procedure

In the second step of the approach, the exact positions of the components are determined under the topological combinations fixed with a constraint-directed search algorithm. This problem can be formulated as an optimization problem, which is shown in the following.

5.1 Formulation

5.1.1 Design variables The design variables relating to a component are defined as shown in Fig. 5. In the figure, six variables, x_{A-}, x_{A+}, y_{A-}, y_{A+}, z_{A-}, and z_{A+}, correspond to the inside positions of the four surrounding walls, ceiling and floor of component *A*. Their outside positions can be calculated from their thickness values. As for the outside walls of a plant building, structural walls and floors, they are dealt with as special components and their positions are also defined in the same way.

In addition to the variables related to components shown in Fig. 5, some 0-1 integer variables are used for formulating the combinational conditions which are explained in the next subsubsection.

For convenience, the direction of the x axis is defined from the west to the east and the direction of the y axis is defined from the south to the north in Fig. 5.

5.1.2 Constraints The constraints are defined for the following conditions.

(1) **Condition on the minimum size of respective component :** If the minimum size of a component is given with the minimum width, depth and height, the constraint is defined by the following inequalities.

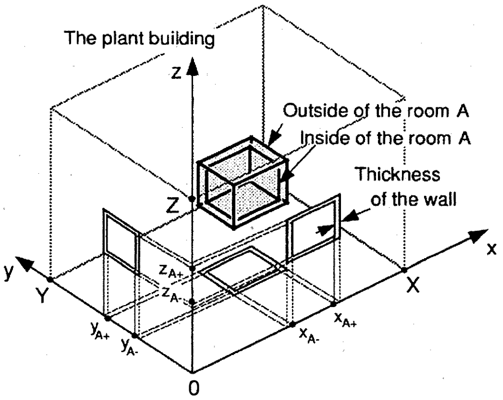


Fig. 5 Design variables related to a component

$$\begin{aligned} & x_{A+}-x_{A-}\geq w_A \\ & y_{A+}-y_{A-}\geq d_A \\ & z_{A+}-z_{A-}\geq h_A \\ & \quad OR \\ & x_{A+}-x_{A-}\geq d_A \\ & y_{A+}-y_{A}\geq w_A \\ & z_{A+}-z_{A-}\geq h_A \end{aligned} \qquad (1)$$

where w_A, d_A and h_A are the minimum width, depth and height of the component A, respectively.

In equation (1), the "*OR*" condition is related to the layout direction of component A. This constraint is translated into the following inequalities by introducing a 0-1 integer variable, $\delta_A=\{0, 1\}$.

$$\begin{aligned} & x_{A+}-x_{A-}\geq\delta_A w_A+(1-\delta_A)d_A, \\ & y_A-y_{A-}\geq(1-\delta_A)w_A+\delta_A d_A, \\ & z_{A+}-z_{A-}\geq h_A \end{aligned} \qquad (2)$$

If the numbers of its compartments are different from each other in the directions of the x and y axes, the above 0-1 integer variable can be fixed before applying the optimization calculation.

If the minimum size is given with the floor area and height, the constraint is defined with the following inequalities.

$$\begin{aligned} & (x_{A+}-x_{A-})(y_{A+}-y_{A-})\geq s_A, \\ & x_{A+}-x_{A-}\geq 0, \\ & y_{A+}-y_{A-}\geq 0, \\ & z_{A+}-z_{A-}\geq h_A \end{aligned} \qquad (3)$$

wher s_A is minimum floor area of the component A.

Moreover, if the minimum size is given with the volume, the constraint is also defined with similar inequalities.

(2) Conditions for maintaining the topological relations fixed in the first step and maintaining the minimum thicknesses of walls and floors : For example, if component A is laid out along the west side of component B, the constraint is defined with the following equality.

$$x_{B-}-x_{A+}=\max(t_A, t_B) \qquad (4)$$

where t_A, t_B are the required thicknesses of the surrounding walls of the components A and B, respectively.

In addition to the above conditions, we must consider how the components which might be touching at their corners are related to each other. Figure 6 gives an example case, where component A might be touching component B at its south-west corner. For this situation, the infeasible combination shown in the middle part of the figure is not acceptable, and one of the three feasible combinations shown in the bottom part must be actualized. This constraint is defined by the following inequalities by introducing a 0-1 integer variable, $\delta_{AB}=\{0, 1\}$, and a positive large number, K.

$$\begin{aligned} & x_{B-}-x_{A+}\geq\max(t_A, t_B)-K\delta_{AB}, \\ & y_{A-}-y_{B+}\geq\max(t_A, t_B)-K(1-\delta_{AB}) \end{aligned} \qquad (5)$$

As for these combinational conditions, in some cases, the value of δ_{AB} can also be fixed before the optimization calculation based on the topological relations among the components and their sizes.

(3) Conditions on the outside walls of a plant building, structural walls and floors : As mentioned before, the outside walls of a plant building, structural walls and floors are also dealt with as components. The constraints on these special components are similar to the other components except for the following two points : In Eq. (2), the inequalities related to their thickness are replaced with equalities, and some of the equalities in Eq. (4) are replaced with inequalities in order to avoid making the optimization problem infeasible.

5. 1. 3 Objective function The primary objective function is to minimize the total size of a plant building. The objective function is defined as follows by adding some artificial penalty terms in order to arrange the spare space :

$$\begin{aligned} \text{Minimize } Z = & \text{ (volume of a plant building)} \\ & +k_1\sum_i(\text{width of a pathway})_i \\ & +k_2\sum_j(\text{floor area of a component})_j \end{aligned} \qquad (6)$$

where k_1 and k_2 are penalty coefficients.

The layout result discussed in section 6 was produced with the coefficients $k_1=0.01$, $k_2=0.001$. These values of coefficients allow for the inclusion of spare space into the components except for pathways.

5. 2 Optimization algorithm

As shown in the above subsection, the optimization problem can be formulated as a mixed-integer programming problem. It has the following characteristics : (1) most of the constraints and objective

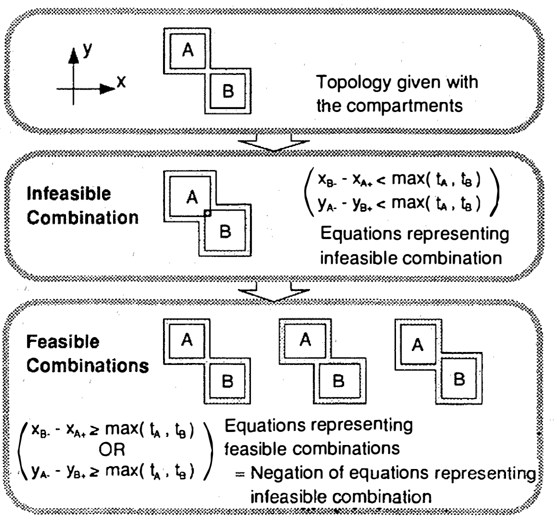


Fig. 6 Combinations related to the corners of the components

function are linear ; (2) the approximate values of the design variables can be estimated from the topological layout result and the approximate size of a compartment ; (3) the formulation includes some 0-1 integer variables. Therefore, we apply a hybrid optimization algorithm combined with sequential linear programming (SLP)(7) and mixed-integer linear programming (MILP)(8).

5. 3 Procedure for determining the exact layout

Figure 7 shows the sequence of the procedures for determining the dimensional layout by applying the optimization technique. The entire procedures are automatically executed in the following way.

First, the mathematical model of the optimization problem is formulated from the layout result of the first step and the other conditions. The equations of the formulation are represented with lists in the LISP language. Second, some heuristics are applied and the equalities are substituted into the other formulas in order to reduce the problem size. As shown in subsubsection 5. 1. 2, some values of 0-1 integer variables included in Eqs. (2) and (5) can be fixed by using the heuristic knowledge and it is necessary for solving the optimization problem in a shorter computation time. Third, the nonlinear formulas such as Eq. (3) are symbolically linearized. Finally, the actual optimization calculations are iterated until the solutions are converged, and then the dimensions and positions of a layout can be determined.

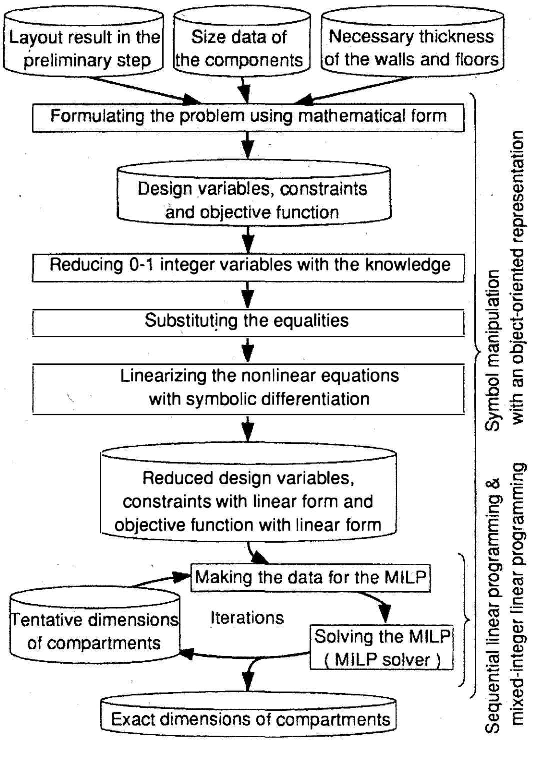
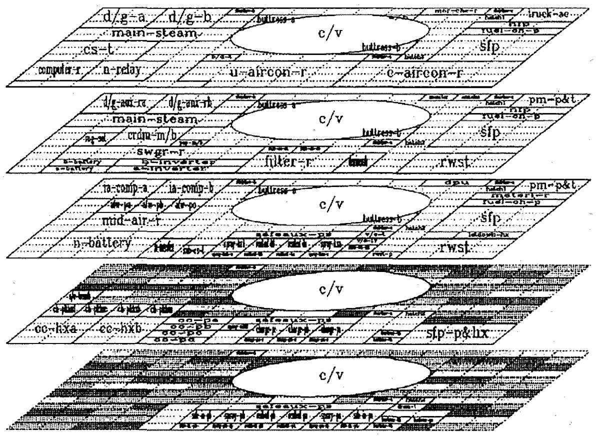


Fig. 7 Procedure for determining the dimensional layout

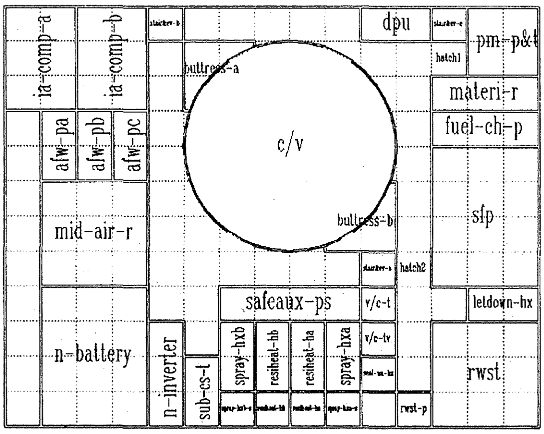
5. 4 Implementation of the approach

The approach described in the above subsections is implemented on a engineering workstation. The procedures for the automatic formulation of the problem and the iteration control of the optimization calculations are written in Common Lisp with an object-oriented programming technique. The routine for the optimization calculation is written in the C language.

If too many 0-1 integer variables are included in the formulation, it may be difficult to solve the optimization problem in a practical computation time. In such cases, the whole problem is divided into subproblems by dividing the whole plant building into subdivisions. Then, the values of the integer variables are initially fixed by solving the subproblems, and the whole problem is solved under these fixed values. In this way, a quasi-optimal layout can be produced. The example result shown in the next section is produced using this method.



(a) Perspective view



(b) Floor plan of the third floor

Fig. 8 The result of preliminary layout

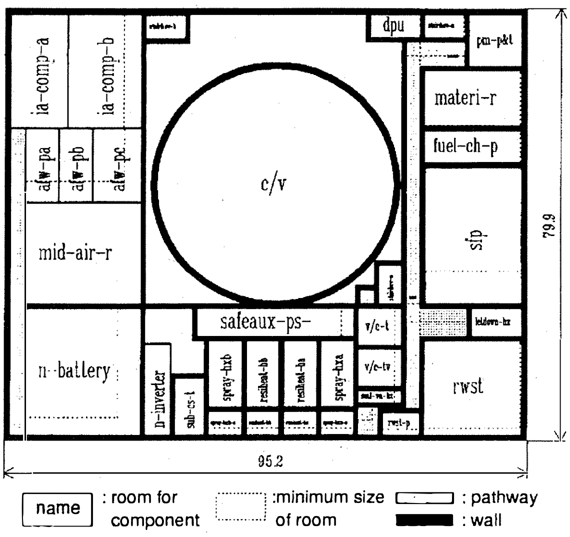


Fig. 9 The result of embodiment layout

6. Application to the Layout Design of a Nuclear Power Plant

Finally we apply the approach to the layout design of a nuclear power plant. Nuclear power plants are usually composed of about 100 components and they are laid out in several floors three-dimensionally. The layout result is shown in the following:

Figure 8 shows the layout result of the first step. Ninety-five components were laid out in the plant building with 5 floors. Two hundred forty spatial constraints as shown in Table 3 are set for this result.

Figure 9 shows the third floor plan of the layout result of the second step. The optimization model for this result includes 791 design variables, in which 40 variables are 0-1 integer variables, 638 equality constraints and 499 inequality constraints.

As shown in the figures, the approach can solve the complicated and large-scale layout design problem of nuclear power plants.

As for the computation time required for this result, the first-step layout shown in Fig. 8 was produced in about 30 minutes and the second-step layout shown in Fig. 9 was produced in about 90 minutes, with Sun SPARC station 2 (28.5 MIPS, 4.2 Mflops).

7. Summary

In this paper, we presented a layout design system with a hybrid approach for spatial layout problems of power plants. The approach is based on the concept that the description of a layout is separated into two parts: the topological layout and the dimensional layout. According to this concept, it is composed of two procedures: the constraint-directed search procedure for the topological layout and the optimization procedure for the dimensional layout. Finally, the system was applied to the layout design of a nuclear power plant and its effectiveness and validity were shown.

Acknowledgments

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