

Title	Automated Acquisition of Constraints in Plant Layout Design Problems
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Citation	JSME international journal. Ser. C, Dynamics, control, robotics, design and manufacturing. 1995, 38(2), p. 334-341
Version Type	VoR
URL	https://hdl.handle.net/11094/3332
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Automated Acquisition of Constraints in Plant Layout Design Problems*

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In layout design, components of a plant must be arranged so as to satisfy various conditions imposed by them. We have presented a hybrid layout design system for power plants by combining a constraint-directed search procedure and a mathematical optimization procedure, in which the layout conditions are declaratively represented as spatial constraints. The contents of constraints prescribed for the layout design system is very important for generating a satisfactory arrangement, and they have been described by the designer's judgment. In this paper, we clarify the causality between constraints and plant configuration, and develop an automated acquisition system of layout constraints using an expert system technology. Finally, the constraints defined with it are examined in the layout design of a nuclear power plant in order to check the validity of causality.

Key Words: Design Engineering, Layout Design, Constraints, Knowledge Acquisition, Expert System, Power Plants

1. Introduction

Layout design, in which the positions of plant components*¹ are determined, is an essential design process of plants such as power plants. However, its process and procedures strongly depend on the designer's expertise, and it is not easy to automate the layout design process using computer systems. In the previous studies⁽¹⁾⁽²⁾, we have developed a layout design approach combining a constraint-directed symbolic search procedure and a mathematical

optimization procedure. In the approach, layout specifications such as space limitation, functional requirements, etc., are declaratively prescribed as "constraints". The system implemented with this approach was applied to layout design problems of nuclear power plants, and its validity and effectiveness were ascertained. The contents of constraints prescribed for the system is very important for producing satisfactory layout results. Therefore, if such constraints are automatically generated, the approach would become more effective for automating the layout design process.

In this study, first we clarify the causality between the layout constraints and the information relating to plant configuration and its components from the viewpoint that the constraints are determined based on the required functions of plant, cost conditions, safety conditions and so on. Second, we describe the causality as "if—, then—" type rules, and develop an expert system for automatically generating the constraints. Finally, we integrate it with the layout design system⁽¹⁾⁽²⁾ which was developed previously, and apply the integrated systems to a case of the design problem of nuclear power plants in order to

* Received 21st October, 1993. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 58, No. 555, C (1992), p. 3449-3454 (Received 14th May, 1992)

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*¹ In this paper, we use the following terminology: 'A layout component' means a facility, i.e., a component of the plant, such as a pump, a tank, a heat exchanger and so on, and it also means the room where it is located.

ascertain their validity.

2. Layout Constraints in Plant Layout Design Problems

As mentioned in the Introduction, the layout design is a process in which the positions of plant components are determined so as to accomplish functions and satisfy the spatial relations among them. We have developed the layout design system^{(1),(2)}, which concept is shown in Fig. 1, and explanations of it are briefly provided in subsection 2.2. The essential characteristic of the system is that the layout specifications are represented as declarative "layout constraints", and that layout results are generated based on such constraints by the layout algorithm.

In this section, the classifications and examples of the constraints and the outline of the layout design system are shown as a preparation for discussing the causality relating to the constraints.

2.1 Characteristics of constraints

In the layout design system developed, the layout specifications are declaratively represented as "constraints" which are independent of the layout procedure. Examples of the constraints are shown below:

- Component *A* is located higher than component *B*.
- Component *A* is located on the highest floor.
- Component *A* is located touching to component *B*.
- Component *A* is located in a different direction from component *B*.
- Component *A* has a pathway to the entrance.
- Component *A* is located close to component *B*.
- Component *A* is located on a higher floor.

These constraints are classified into two types from the viewpoint of how they restrict layouts:

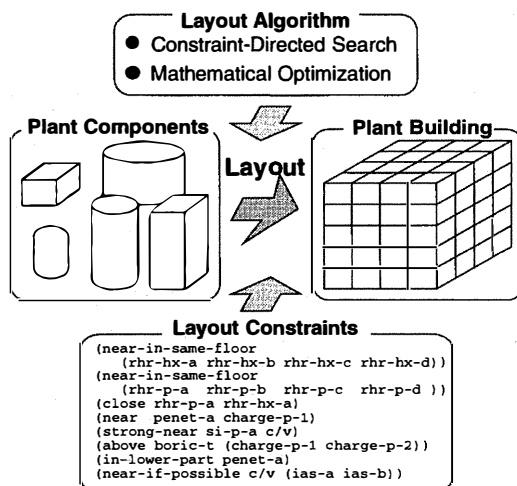


Fig. 1 Plant layout design process

● **Obligatory type**: The constraints which strictly specify a layout. They indicate whether each layout candidate for a component is acceptable or unacceptable. They correspond closely to the functional requirements of the components.

● **Suggestive type**: The constraints which weakly specify a layout. They suggest whether each layout candidate of a component is superior or inferior to other layouts from the viewpoint of spatial relationships. They usually correspond to the satisfaction level of the conditions for simple operation, ease of maintenance, plant cost, etc.

This classification is important and essential for the layout algorithm as shown in the next subsection, since the former are used for tree pruning and the latter for evaluating the respective layout candidates in the search procedure. Moreover, the separation of the design specifications from the layout procedure is useful and meaningful for clarifying the contents of the layout design process.

2.2 Outline of layout design system

Corresponding to the above constraints, the positions and directions of the components must be determined so as to satisfy them in the layout design problem.

In the approach^{(1),(2)} developed, the layout space where the components should be located is represented as a set of modular units called "compartments" with a unique cubic space, and the size and shape of each component are also represented with a number of compartments. Based on this representation, the layout design process is separated into the following two subprocesses:

(1) **The preliminary process**: The process determining the topological relationships among plant components so as to satisfy some layout constraints. In this process, a layout is represented by the assignments of the compartments of respective components to the corresponding set of ones in the plant building.

(2) **The embodiment process**: The process determining the exact positions and sizes of plant components so as to minimize the plant size. In this process, the layout determined in the preliminary subprocess is finalized by determining the actual sizes of the compartments under the fixed topological relations.

The procedures of the subprocesses are briefly explained in the following subsections, respectively.

2.2.1 Preliminary layout process In the preliminary process of the layout design system, the topological relations among plant components are determined by assigning respective components to corresponding sets of compartments. In order to

achieve this process, we apply a symbolic and constraint-directed search procedure in order to find a satisfactory one of feasible layouts⁽¹⁾.

Figure 2 shows the depth-first search tree of this search problem. In the tree, the top node corresponds to the initial state where no component is located, and the bottom nodes are layout solutions where all components have been located. In the search procedure, the plant components are located in the space of the plant building sequentially from the top node to the bottom nodes.

In the first step of the preliminary process, the components are sorted according to the sequence in which the layout operations will be carried out. This sequence is determined by considering several kinds of constraints among the components. When the sequence is sorted, the following factors are also taken into consideration in order to efficiently carry out the search operations: the size of components, the number of constraints related to a component and the sequences of their relationships.

In the second step of the preliminary process, the search operation for each component is executed in the sequence determined in the first step. The searches are performed continuously with a depth-first strategy, while backtrack operations are carried out if needed. When the layout of a component is determined, first, a list of candidate compartments is produced by checking the first kinds of obligatory constraints. Second, they are combined into candidate locations corresponding to its shape. Third, the candidate locations which are checked with the second kinds of obligatory constraints are sorted further according to suggestive constraints and some heuristics. Finally the component is laid out in the candidate location with the first priority, and it is then tested against the last kinds of obligatory constraints, while the rest of the candidates are stored for use in backtrack operations. These operations are iterated

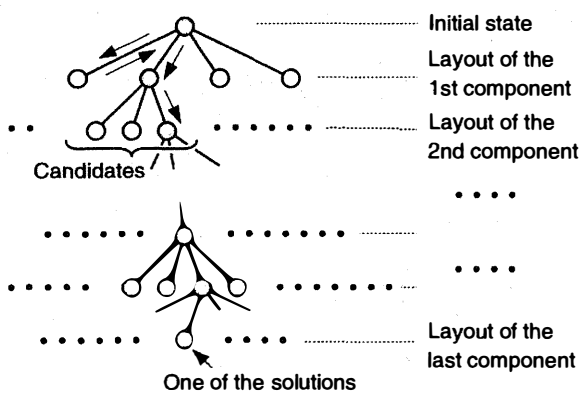


Fig. 2 Search tree in preliminary layout

until all of the components are given locations.

2.2.2 Embodiment layout process In the embodiment process of the layout design system, we apply a mathematical optimization procedure to the topological and combinatorial layout result obtained with the above search procedure in order to finalize the layout by determining the actual sizes of the respective components⁽²⁾.

The formulation of the optimization problem here is summarized as follows:

Design variables: The positions and sizes of components and their directions are taken as the design variables. As for the component A , its position is defined by the six variables, x_{A-} , x_{A+} , y_{A-} , y_{A+} , z_{A-} and z_{A+} , in the orthogonal coordinate system as shown in Fig. 3, and its direction is defined by a 0–1 integer variable, $\delta_A = \{0, 1\}$.

Constraints: Constraints are introduced for the following purposes:

- In order to maintain the minimum size of the room for each component.
- In order to maintain the topology of the compartments during the optimization procedure; that is, to avoid any overlap of the components. Also, in order to maintain the required thickness of walls and floors.
- In order to set the thickness of some special components, such as structural walls, exterior walls and total-floors of the building, at the necessary values so as to satisfy the conditions for structural strength.

Objective functions: The objective is to minimize the total size of the plant building which is related to the plant construction cost.

As a result, the problem is formulated as a mixed-integer programming problem, and most of the constraints take the form of linear equations. Moreover, the approximate value of each design variable, except for the 0–1 integer variables, results from

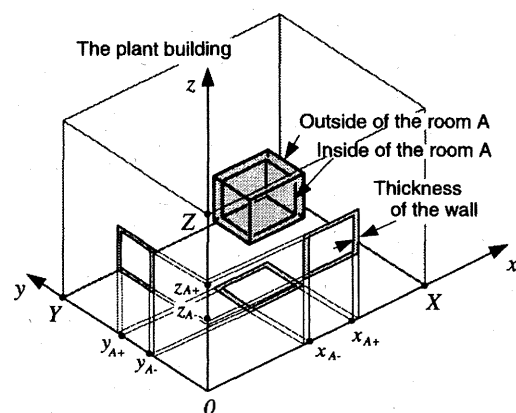


Fig. 3 Design variables related to a component

the preliminary layout process. We apply a hybrid procedure of sequential linear programming (SLP)⁽³⁾ and mixed-integer linear programming (MILP)⁽⁴⁾ for this optimization problem.

Using the optimization procedure explained here, the layout design can be finalized.

2.3 Prescription of constraints

As aforementioned, one of the advantages of the layout approach is that the layout specifications are clearly represented as constraints which are separated from the layout procedure itself. This separation also facilitates clarification of the contexts of the layout design procedure. However, it is difficult for a designer to set up such numerous proper constraints even if he is very experienced, because these constraints include various kinds of underlying information. The prescription of constraints would be one of the difficulties in applying the layout approach to actual problems.

In this paper, in order to overcome this difficulty, we discuss how the constraints can be automatically prescribed for the layout design system. In the following sections, the concept for automatic acquisition of the constraints, the knowledge which is necessary for it, the expert system based on the concept, and its application to the design case of a nuclear power plant are explained, respectively.

3. Automated Acquisition of Constraints

As mentioned in the previous section, it is difficult for a designer to set up such numerous proper constraints for use in the layout design system^{(1),(2)}, even if he is a very experienced designer. Such constraints are originally recognized to be prescribed with the intention of accomplishing the required functions, suitable cost and so on in a layout result, and they are thought to be related to the plant configuration and the functions of respective plant components. Therefore, if the causal relationships between the constraints and the plant configuration are revealed, then the constraints can be generated from the description of the plant and its components.

As for the plant configuration and respective components, they are a collection of facts which can be prescribed much more easily than the constraints, because they are immediately derived from the design result of the plant configuration. This knowledge is modeled with entity-and-attributes relationships, and it can be represented with a frame-type representation method^{(5),(6)}. As for the causality, it is strongly dependent on the physical laws, designer's experience, etc. In order to prescribe such causality, some investigations are required, which will be discussed in section 4. Since the causality is the knowledge for transform-

ing the factual knowledge into the constraints, it is thought to be suitable to represent it by using the "if—, then—" rules^{(5),(6)}. By integrating these frame-type knowledge and production rules, it is possible to develop an expert system^{(5),(6)} for automatically generating the constraints, which will be explained in section 5. In this study, the expert system is developed for practical layout design problems of nuclear power plants in order to ascertain the validity of the concept proposed and the causality investigated, which will be demonstrated in section 6.

Besides, if the causality relating to constraints is revealed through the process developing the expert system, the contents and meanings of layout design and layout conditions will be further clarified.

4. Knowledge for Generating Layout Constraints

In this section, we discuss the contents of plant configuration and their components and the causal knowledge for generating the layout constraints.

4.1 Plant configuration and its components

Various kinds of data and knowledge are dealt with in the plant design process. The following contents relate to plant configuration and its components, and they are considered to be already fixed before the layout design process.

- **Attribute information of plant components such as kinds and sizes**: The attribute information of each plant component such as its kind, size, the name of the subsystem to which it belongs, and so on.
- **Systematic relationships among components through pipes, and properties of contents in them**: Figure 4 shows a part of the plant schematic diagram for a case of nuclear power plants. In the figure, the components are represented with typical icons, and the systematic connections through components with pipes or ducts are represented with lines. Moreover, the diameters of pipes and the physical properties such as pressure,

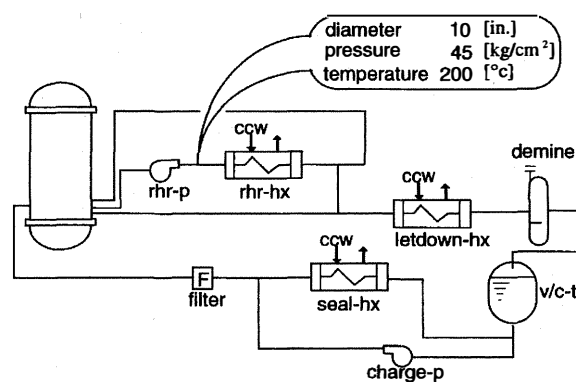


Fig. 4 Plant schematic diagram

temperature, etc. of the contents are attached to the lines.

● **Size and configuration of plant building:** The approximate size, the number of floors, etc. of the plant building where the components will be located. These are closely related to plant layout and it should be determined in the layout design process. However, since it will be assumed to be temporarily fixed in the practical layout design process, it is considered to already be known here. These can be used as the object knowledge when the constraints are generated. They are represented with the frame-type knowledge representation method in the expert system mentioned in the next section.

4.2 Causality for generating layout constraints

As discussed in the previous section, the layout constraints can be generated from the object knowledge relating to the plant and its components. The causal knowledge for generating the constraints can be classified into two groups: knowledge relating to cost conditions and knowledge relating to plant functions. The latter are furthermore classified into two subgroups: knowledge relating to functions of the respective components and knowledge relating to functions of the respective subsystems. In the following subsections, contents and purposes of these causality groups are discussed, respectively.

4.2.1 **Causality relating to pipe lengths and so on** In the layout design of plants, the primary objective is to minimize the cost of plant itself. Among the cost factors, the cost of pipes is very much affected by the layout result, because the lengths of pipes are strongly dependent on the layout positions of components. It is necessary that the components which are connected with expensive and thick pipes should be located close to or touching each other.

For example, in the case of nuclear power plants, the following criteria are applied to generate constraints, which are expected to decrease the cost of pipes.

- If the pressure and radioactive level in a pipe are high, then the components connected by it should be located touching each other.
- If the pressure is moderate, the radioactive level is low, and the temperature is not high in a pipe, then the components connected by it should be located close to each other.

Since these criteria are independent of the respective components and subsystems in plants, they are so general that they can be applied to various kinds of plants.

4.2.2 **Causality relating to operations of plant components** It is necessary that respective components to be located fulfill the corresponding functions.

For this purpose, some components should be located in specific positions or in specific spatial relationships.

As for the respective components, the following criteria must be taken into consideration. Additionally, their reasons and purposes are enclosed by parentheses, respectively.

- Tanks such as storage tanks should be located in the lower part of the building. (In order to keep the efficiency of collecting liquid higher.)
- The pump for drawing out the liquid stored in a tank should be located lower than the corresponding tank. (In order to keep net positive suction heads to a proper value.)
- The room of a diesel generator should be located touching the outside of the building with its shorter edge. (In order to facilitate carrying of the generator into the room and its maintenance.)

Since most of these causalities can be prescribed for the kinds of components and not for the individual components, they also can be widely applied to various kinds of plants.

4.2.3 Causality relating to functions of plant subsystems

The components of the plant, that is, machinery and equipment, operate in a cooperative fashion in order to fulfill all of the plant's required operations. Therefore, some groups of the components make up subsystems of the plant corresponding to their functions and operations. The components of a subsystem have some special relations to each other and the following causality must be taken into consideration similar to the individual components.

- The components of a subsystem should be located close to each other. (In order to keep manipulation and maintenance easy.)
- The subsystems relating to the central control room should be located close to each other in a much higher part of the plant building. (In order to keep them away from damp environments and avoid intersection with other pipes, because the subsystems include many electric devices.)
- The drainage subsystem should be located in the lower part of the plant building.
- The subsystem related to cooling water should be located on the side of seawater. (In order to shorten the seawater pipes.)

In comparison with the former two groups of causalities, these are dependent on the characteristics of the respective subsystems. Therefore, they cannot be applied to all kinds of plants, while they can be applied to a specific type of plants.

4.2.4 Causality relating to layouts and constraints

In addition to the above constraints, the conditions which are inherent in the layout design problem itself should also be taken into consideration.

For example, a series of components should be located in a row in some cases. However, these are not related to the plant configuration and functions, and they cannot be generated from the description of the plant. Consequently, these constraints are omitted from the scope of automatic generation.

On the other hand, some constraints generated with the causality mentioned above would conflict with each other or would too greatly restrict the layout. In order to prevent those conflicts and over-restrictions, the knowledge such as converting overly strict obligatory constraints into suggestive ones is necessary. In this paper, this knowledge is called "rules for checking constraints".

4.3 Rules for generating layout constraints and their generality

As the above causal knowledge is practically checked for some types of nuclear power plants, the rules for generating the constraints are obtained, as shown in Table 1. These rules can be applied to some types of nuclear power plants, including the case shown in section 6, and they would be widely general rules for plant design problems. However, as aforementioned, some of the constraints are strongly dependent on the individual cases, and it is thought to be difficult to be represent such causality as rules. Consequently, additional handling of those constraints would be necessary for individual plant types.

5. Expert System for Generating Layout Constraints

5.1 Architecture of the expert system

We develop an expert system for generating the layout constraints by representing the causality discussed in the previous section as production rules^{(5),(6)}. Figure 5 shows the architecture of the expert system, which consists of the production system, knowledge base and data base. The knowledge on the causality discussed in the previous section is represented as rules in the knowledge base. The information on plant configuration and its components is represented as object-oriented⁽⁷⁾ frames^{(5),(6)} in the data base. The layout constraints which will be generated on the working stage of the production system are also stored in the data file, and they will be used in the layout design system⁽¹⁾.

The expert system is implemented in COMMON LISP⁽⁶⁾ on an engineering workstation, Sun SPARC Station.

5.2 Representation of plant and its components

Knowledge relating to the plant, its components and the connections among them is represented with the frame-type knowledge representation method, which is combined with the object-oriented program-

ming technique. The object-oriented technique is widely used in computer applications because of the advantages in its programming method based on modularity and hierarchy.

Figure 6 illustrates the outline of the representation method with class objects and instance objects. The 'class objects' are hierarchically classified with superclass-subclass relations corresponding to the kinds of the components. The respective 'instance objects' represent the actual components and pipes, in which their attribute information is represented as 'instance variables'. The connections among the components with pipes and ducts are represented as the 'associations' between such instance objects. This

Table 1 Rules for generating constraints

Kind of Rules	Number of Rules
Rules relating to plant cost	12
Rules relating to component operation	53
Rules relating to subsystem functions	32
Rules for checking constraints	14
Total	111

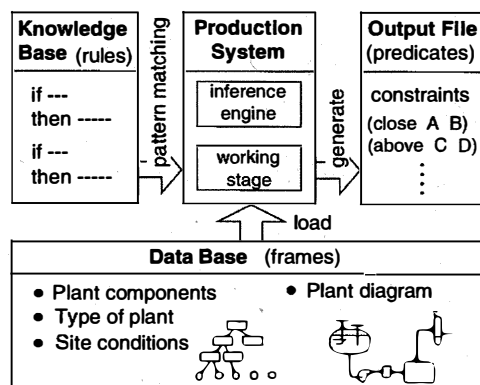


Fig. 5 Architecture of the expert system

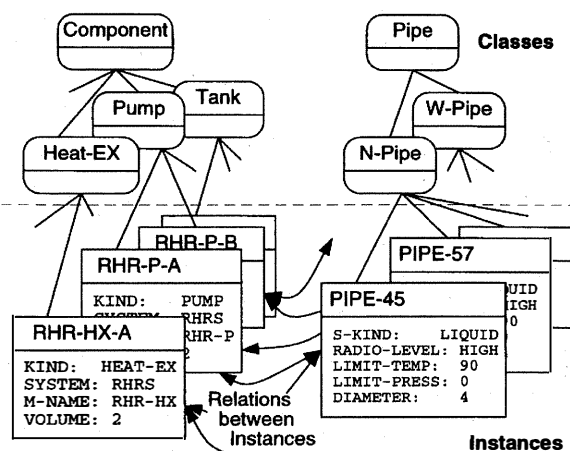


Fig. 6 Representation of plant and its components

representation method is effective for description of the production rules mentioned in the next subsection.

Besides, since this representation method with frames is too complicated for users to directly describe, the system has an interface function by which the frame-type representation can be generated from another declarative representation in a data file.

5.3 Representation of causality for generating constraints

The causal knowledge for generating the constraints is represented by the "if—, then—" type knowledge representation method, as aforementioned.

Figure 7 shows some examples of the rules. For example, 'rule2' indicates that if the kind of tank is a storage tank (store-tank) and it does not belong to the subsystem for liquid wastes, then the tank should be located in the lower part of the plant building (strong-in-lower-part).

The description of these rules includes the reference of the plant components, which are represented as the instance object as mentioned in the previous subsection. The causality in the rules is related to the kind of components and not to the individual components. Therefore, the inference engine of the production system has the ability to refer to all of the individual components belonging to the kind of components by indicating them with the name of the class object in the rules. As a result, the rule can be applied to all of the components relating to the class object.

The rules are also categorized into some rule blocks corresponding to Table 1, and the sequence in which the respective rule blocks are applied is defined beforehand. The reasons for the categorization are that the causality is classified into some groups as discussed in the previous section, and that some rules are defined based on the premise that some other rules

```
(rule1 :
  if (&eq (&get pipe radio-level) 'high)
    (>= (&get pipe limit-press) '20 )
    (>= (&get pipe limit-temp) '100 )
  then (&create-predicate
        (: close area1 area2)) )

(rule2 :
  if (&eq (&get tank 'kind) 'store-tank)
    (&not (&eq (&get tank 'system) 'ws))
  then (&create-predicate
        (: strong-in-lower-part tank)) )

(rule4 :
  if (&eq system 'w1)
  then (&create-predicate
        (: strong-near-if-possible
          (&get-association system
            'consist-of))) )
```

Fig. 7 Examples of rules for generating constraints

have already been applied. The categorization of rules into rule blocks also greatly improves the efficiency of inference.

6. Application to Nuclear Power Plants

Finally, the expert system is applied to layout design of a nuclear power plant. In general, a nuclear power plant consists of about one hundred components, and they are located in a three-dimensional way on the several floors of the plant building. As for the layout constraints, the conditions relating to cost, plant operation and so forth must be taken into consideration.

In this example, the plant consists of 79 components, which must be located in the plant building with five floors. The 563 layout constraints are generated by the expert system developed. Figure 8 shows a part of these constraints. Compared with the ones which are generated by the experienced designer, the total number of which is 179, it is ascertained that they include all of those which are necessary for producing suitable layout results although they include redundant ones. The reason why the system generates the redundant constraints is explained as follows:

- In the case of the expert system, many suggestive constraints, such as that component *A* should be located close to component *B*, are automatically generated.
- In the case of experienced designers, they do not generate suggestive constraints between the components which have other obligatory constraints.
- The system tends to blindly generate such suggestive constraints, although other obligatory constraints dominates each of them.

Furthermore, the constraints generated by the expert system are used in the layout design system^{(1),(2)}, which was briefly explained in subsections 2.2.1 and 2.2.2. Figure 9 shows a perspective view of the preliminary layout result and Fig. 10 shows a floor plan of its third floor. As compared with the layout result which is produced with the constraints generated by the experienced designer, the layout result is ascertained to be

```
(near-in-same-floor
  (rhr-hx-a rhr-hx-b rhr-hx-c rhr-hx-d))
(near-in-same-floor
  (rhr-p-a rhr-p-b rhr-p-c rhr-p-d ))
(close      rhr-p-a      rhr-hx-a      )
(near      penet-a      charge-p-1    )
(strong-near si-p-a      c/v          )
(above     boric-t      (charge-p-1 charge-p-2))
(in-lower-part penet-a      )
(near-if-possible c/v      (ias-a ias-b))
```

Fig. 8 Examples of generated constraints

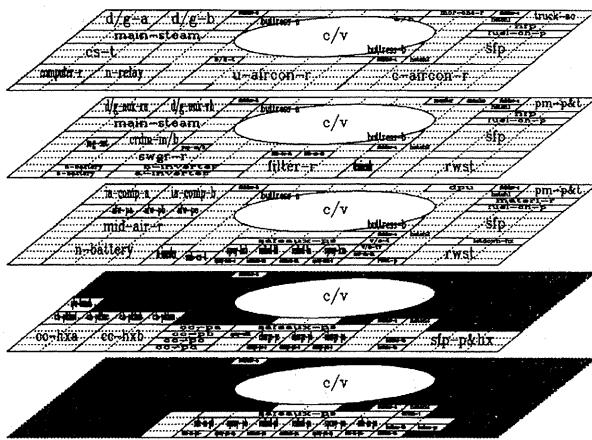


Fig. 9 An example of preliminary layout results—Perspective view

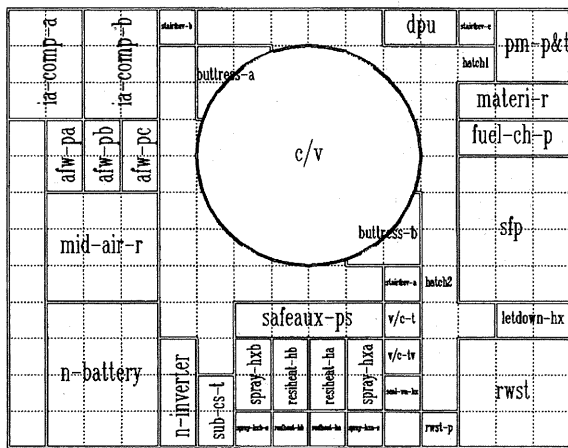


Fig. 10 An example of preliminary layout results—Floor plan

satisfactory as a whole. Followed by this preliminary layout, the embodiment layout is generated using the optimization procedure. Figure 11 shows the result with its third floor plan.

In addition to this example, we successfully applied the expert system to several other plants.

7. Conclusions

In this paper, we discussed the contents of layout design knowledge, especially the layout constraints, and studied the causality between the layout constraints and the systematic configuration of a plant. Based on this investigation, we developed an expert system for automatically generating the layout constraints by representing the causality as production rules. The validity and effectiveness of the system were ascertained through its applications to some

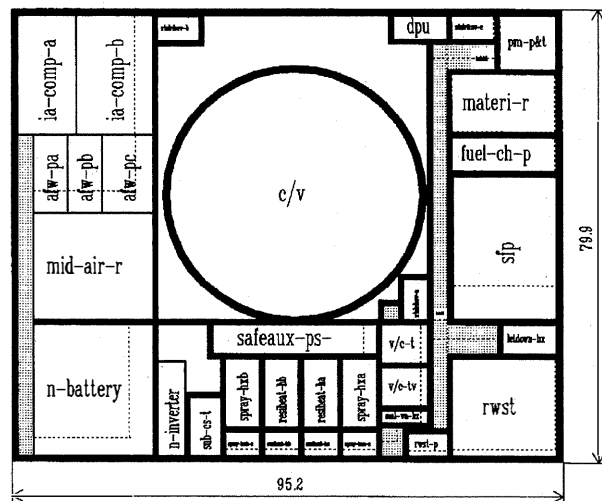


Fig. 11 An example of embodiment layout results—Floor plan

design cases of nuclear power plants.

We thank Tetsundo Nakatogawa and Makoto Takeuchi of Mitsubishi Atomic Power Plant Industries Inc. for their helpful instruction on the actual design of nuclear power plants during the implementation of the system.

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