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An expert system to generate associativity data for layout design

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In this paper we present an intelligent system which assists the layout designer in producing associativity data as input to an automated layout generation tool. The approach which we adopt combines techniques based on expert systems, object-based data structures and cluster analysis. The system eliminates manual input for the associativity data. The object data structure assures data consistency. The cluster analysis determines the strength of relationship between any two pieces of equipment. The expert system provides guidance for the subjective part of the layout design. This results in automation of associativity data generation, an improved user interface, and consistency and accuracy of data. The concept is illustrated by an example taken from the petrochemical industry. © Elsevier Science Ltd. All rights reserved.

Key words: layout design, clustering, expert system, object-based paradigm.

1 INTRODUCTION

Large-scale engineering design often requires the selection and arrangement of bought-in equipment, for example, when designing a process plant. Prior to incorporating the physical sizes and shapes of equipment into the spatial layout design, associativity data which determine the placement of the equipment have to be generated. The process flow diagrams (PFD) specify for the equipment's connectivities, and are an important source of information during the layout design process. However, the information provided by the PFD is not sufficient to become a direct input for layout design. Due to the nature of the design process at this stage (that is, the engineer is mainly concerned with performance), specifications of the equipment that are issued by engineers only include major functional parameters (e.g. working temperature, working pressure). There is no clear indication of the physical sizes of equipment or relationships between pieces of equipment apart from connectivity. The dimensions of a pieces of equipment cannot be obtained until the engineers have sized it and determined the selection criteria (e.g. cost, quality and safety). The specifications from the PFD allow the appropriate pieces of equipment to be selected from suppliers' equipment catalogues. These catalogues include the physical size of every piece of equipment which can be used in the layout design process. In this paper we do not discuss

fabricated work which usually involves negotiation with the subcontractor.

The performance of the layout design process is significantly improved if the input data reflect the need for adjacencies or to preclude adjacency. For example, a desired adjacency might result from the need to ensure a minimum length of connectivities in the production system. Conversely, it may be necessary to ensure that for safety reasons, an item of equipment needs to be widely separated from another one. Adjacency constraints are generally produced as a result of equipment clustering, performed in order to optimise (in fact, to best compromise) global parameters and requirements such as safety, serviceability, cost and so forth. Three main types of clustering criteria can be identified, based on connectivity, common function and common process/system, although the list can be expanded if, for example, other important factors such as safety are considered. Furthermore, those two approaches are quite subjective, as they depend upon the engineer's past experience to determine the strength of the equipment relations. In addition, as they follow the method of linear assignment, the users need to enter a large amount of data ($n^*(n\text{-}1)/2$; where n is the number of items of equipment). In this paper, we describe an approach which combines three techniques; namely expert systems, object-based data structures, and cluster analysis in an attempt to solve these problems.

Section 2 discusses the importance of associativity

Key:

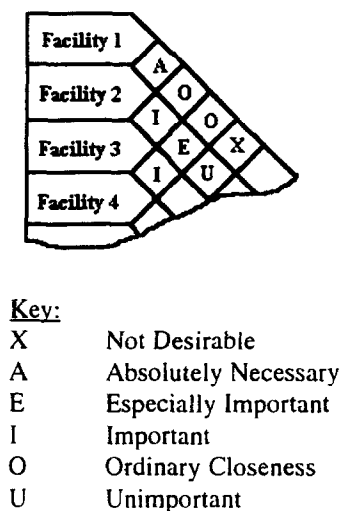|	
X	Not Desirable
A	Absolutely Necessary
E	Especially Important
I	Important
O	Ordinary Closeness
U	Unimportant

Fig. 1. Muther's REL chart.

data in layout design. Section 3 introduces the methodologies used in this work. Section 4 outlines the implementation of the system including an example. The results of system implementation and evaluation are presented in the same section. Section 5 outlines areas for future work. Conclusions are drawn in section 6.

2 THE ROLE OF ASSOCIATIVITY DATA IN LAYOUT DESIGN PROBLEM

Levy[1] introduced the cross chart or 'from–to' chart to the layout design problem. His work has had a great influence on much of the later work in this field. The 'from–to' chart is essentially a square, non-symmetrical matrix whose elements represent the values of flow that pass between two work centres. The REL chart, the development of which was based on this concept, was introduced by Muther[2] in 1955 (see Fig. 1).

This chart represents the closeness demands of a problem in a simple triangular matrix format. Closeness demand is a term used to express the relational strength of one particular facility to any other facility. Since it emerged, the concept of the REL chart has become the basis of layout design techniques. One of the most popular mathematical approaches in layout design is the graph theoretic approach[3] which develops a plan to satisfy the closeness demands of a REL chart. Systematic layout planning (SLP)[4], ALDEP[5] and CORELAP[6] are all based on the closeness demand to solve layout design problems.

An extensive assignment of subjective values in REL charts epitomises the lack of the quantitative approach prior to the employment of locational attributes (in clustering analysis). A locational attribute approach is a rectangular matrix with the *x*-axis representing locational attributes and the *y*-axis representing activity units. The locational attributes are imperative statements relating to the locational properties of activity units. The activity units are arbitrarily sized places

Fig. 2. W. Mitchell's locational attributes matrix.

which are comprised of specific properties in order to accommodate specific activities. Each matrix cell is the intersection of an activity unit with a locational attribute (see Fig. 2). The approach is based on the comparison of a set of locational attributes for each pair of subdivisions. The clustering can be achieved by calculating a numerical value of similarity between the two subdivisions of concern.[7]

This approach was originally designed to be used within the layout design process of functional spaces. Cleland's work[8] was based on this concept and aimed to improve its application in order that it can be used in the layout design process of industrial plant. He considered the object clustering in the context of artificial intelligence and included the locational attributes associated with hazard category and noise potentials along with other conceptual categories such as functions, systems and connective groupings.

The problems of the engineers assigning subjectively large numbers of associativity values are based on their past experiences, for designing a complex plant. It requires a method of automatically generating associativity data to assist engineers. The locational attribute approach can be applied into plant layout design, for determining the strength of equipment relationships. Cleland[8] improved the locational attributes by including conceptual categories, and giving weightings to the grouping types. The strength of the relation between any

two pieces of equipment is measured by a distance between points in a multiaxes coordinate system (see Table 1 and section 3.3).

3 APPROACHES TO GENERATING ASSOCIATIVITY DATA

In the proposed system three techniques are employed: expert systems, the object-based paradigm, and locational attributes. The expert system assists the engineer in selecting appropriate equipment and/or grouping equipment into different categories for the cluster analysis. The object-based data structure maintains the consistency of the information while reducing the input required from the designer. The cluster analysis which is associated with locational attributes and equipment adjacency constraints, determines the strength of equipment relations. The following sections discuss in more detail these three techniques.

3.1 Expert system

An expert system is a computer program which represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice. It solves problems by heuristic or approximate methods which unlike algorithmic solutions, are not guaranteed to succeed.[9] The expert system usually forms its selections by employing an inexact reasoning technique or a matching evaluation function.[10] The expert system, therefore, can be applied when solving problems which are incomplete or in deciphering ambiguous requests. When selecting equipment, users quite often offer only vague requires (e.g. high quality, low cost or high safety). The engineer must then interpret these demands into quantified or qualified factors by using their professional judgement before advice can be given. These criteria can be represented by production rules which are held within an expert system. Moreover, the constraints of equipment adjacency can be easily represented by utilising these production rules. If, for example, it is desirable to cluster together all coolers (heat exchangers) working within a particular temperature interval (say less than 200°C), we can represent this by the rule:

> if: instances of PFDequipment. Type == "cooler" and instance of PFDequipment. Working_Temperature <= 200 then:
> gas_cooler.neighbour+ == object name (instance of PFD equipment);

In this research, the authors utilised production rules and forward reasoning to classify the equipment by quality, cost and safety, grading these criteria into different levels, in order to select the appropriate equipment from suppliers' catalogues, and to divide the PFD into different subprocesses.

Table 1. Distance measurement

$$D_{ij} = \left\{ \sum_{K=1}^{P} (X_{ik} - X_{jk})^2 \right\}^{1/2}$$

D_{ij} = similarity of i_{th} and j_{th} equipment
P = number of locational attributes
X_{ik} = weighting of i_{th} equipment and k_{th} attribute
X_{jk} = weighting of j_{th} equipment and k_{th} attribute

3.2 Object based data structure

Frame or object based data structures can be used to store the characteristics of an object in a structured object which is relatively easy to both use and maintain.

Object based data structures are used in this work to model the connectives, weightings of locational attributes, equipment function and production systems, because they have the following advantages: they are easy to use; the structure of the domain upon which the knowledge is modelled is directly reflected in a knowledge base. The inheritance mechanism allows the knowledge extension. The conjunctions of slots describe objects' properties.

In this work, items of equipment in PFDs and their connectivities are represented in an object based data structure. We define a connectivity class which contains the stream number of in-flow pipes, out-flow pipes, and material in the pipes. The specifications (e.g. working pressure, dimensions, weight and working temperature) of the equipment obtained from the PFD and suppliers' catalogues are also described in the objects.

3.3 Locational attributes and clustering

After the user has given the locational attribute values, an improved locational attribute method is employed. The users assign the preference which is then transformed into different weightings to determine the layout design type and how it is arranged. The information held within the locational attribute matrix can be used for grouping activity units or pieces of equipment based upon the level of similarity which exists between their characteristics. The most commonly used term for this sort of classifying procedure that seeks to gather the component data into groups is *cluster analysis*.[11] The strength of equipment relationship, the associativity data, can be produced by the application of a distance measure, as shown in Table 1.

4 IMPLEMENTATION

A gas processing system for an off-shore oil production platform (see Fig. 3) has been used as an example to demonstrate the effectiveness of the generating associativity data system. The tool employed for its implementation is an expert system shell, Kappa. This includes an object based knowledge representation and a rule based language which allows users to manipulate the desired
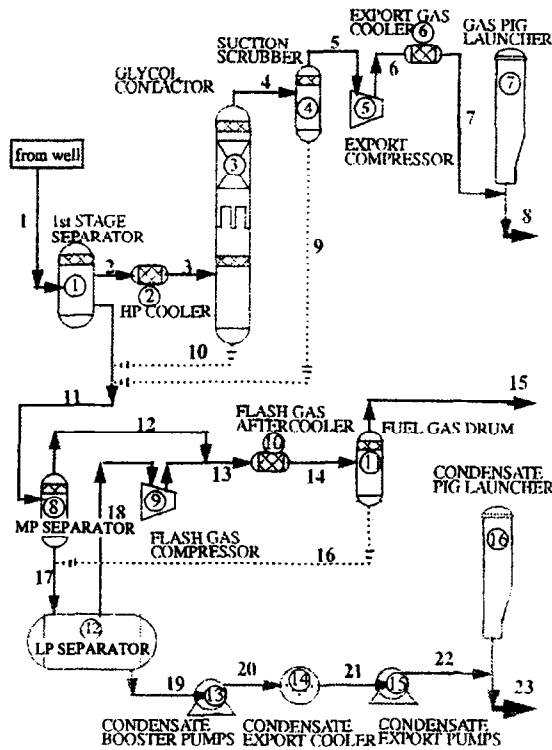
Fig. 3. A PFD of gas processing system.

knowledge. It also incorporates C language to support the solution of procedural problems. We express the PFD, suppliers catalogues and PFD sub-systems in an object based data structure (shown in Fig. 4).
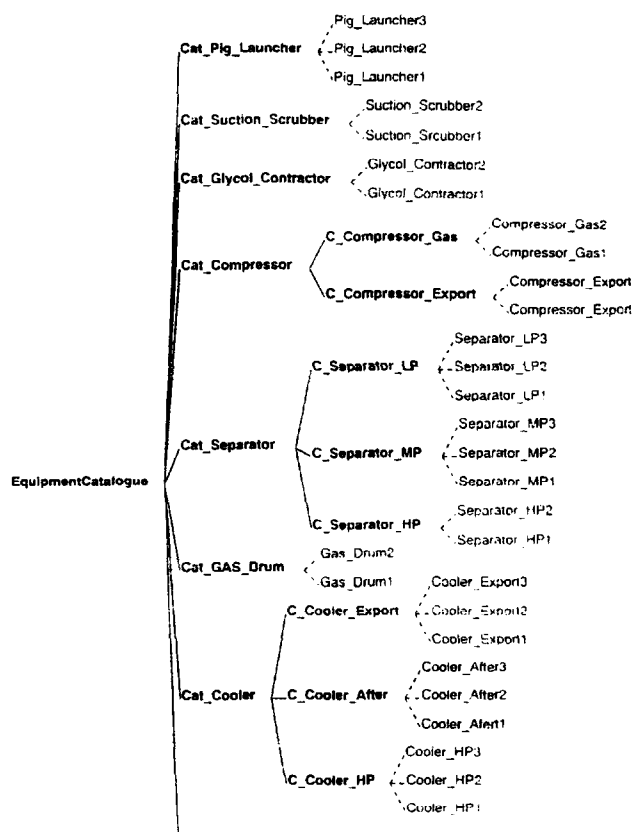

Fig. 4. A PFD represented by object based data structure.

The combination of the specification requirements, with cost or safety preferences, can be considered as constraints. These can be represented as rules in order to support the acquisition of appropriate equipment.

The acquisition of equipment is determined according to the prices set by suppliers and the functionality which the appliance offers. Choosing a piece of equipment based on the price/performance may require relatively specialist knowledge or experience. Rules 1-3 below illustrate how appropriate equipment is selected as an instance of the equipment in the PFD.

frule Rule1
IF instance of boosterpump.price_per_unit >1000;
Then
instance of boosterpump.cost_level = high;
frule Rule2
IF ?preference is cost;
Then
decide.preference = cost;
frule Rule3
IF decide.preference == cost;
?Equipment.specification==?PFD_Equipment_
Specification;
?Equipment.cost_level== high;
Then
instance of PFD_Equipment_Specification+ == ?
Equipment

The qualified equipment instances as found in the suppliers' catalogue become the instances of that piece of equipment class in the PFD. These instances can inherit the properties from parent classes (see Fig. 5).

The PFD can be decomposed into subprocesses on the basis of connected streams with the same material and/or thermodynamic properties. Thus looking at Fig. 3, three gas-condensate subprocesses (high, medium and low pressure) can be identified, where the starting points are the corresponding separators. A piece of process equipment then belongs to a subprocess if it is a part of a stream belonging to that subprocess. Simplifying this assumption for illustration only (Fig. 3), we can 'attach' a piece of equipment to a subprocess if it is a part of a sequence of connected pieces of equipment, starting with a particular separator and tracing say the lighter fraction (gas) path. The following rules show how this can be implemented in a expert system.

frule Rule A
IF
?connect = instanceof Connect;
?Equip = direct subclassof Separator;
?Equip.PFD_Equipment_Name == HP_Separator;
?connect.output == ?equip.PFD_Equipment_No;
?connect.Material == Gas;
Then
direct subclassof SubProcess1+ == ?equip;
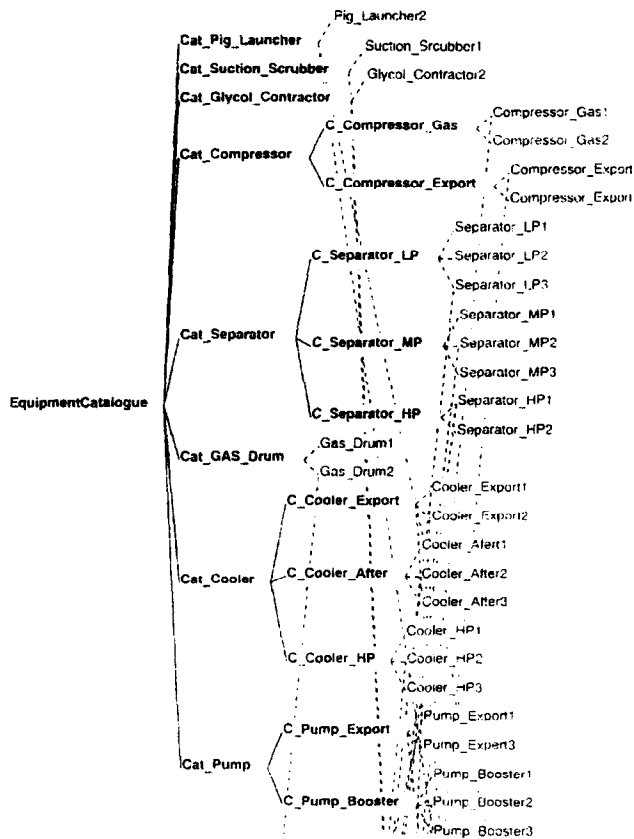temp.connect_to = ?connect.Input_To;
frule RuleB

Fig. 5. Selection and classification of equipment.

IF
?equip = subclassof PDFSpecification;
?connect.Material == Gas;
?connect.Output_From == temp.connect_to;
?connect.Output_From == ?equip.PFD_Equipment
_No;
?equip.PFD_Equipment_Name == HP_Cooler;
Then
temp.connect_to = ?connect.Input_To;
direct subclassof SubProcess1+ == ?equip;

The equipment instances in suppliers' catalogues will be linked to the system to which the equipment belongs (see Fig. 5).

The locational attributes in our case are connectivities, functions, processes and characteristics of the equipment. The activity units are the pieces of equipment contained in subprocesses in the PFD. A process which contains detailed locational attributes is a major factor in designing a layout. The engineer must designate these detailed locational attributes in a class which can be inherited by the subprocess and each piece of equipment. If there is any apparent point of conjunction, then this means that there is a relation between them: 1 for occurrence, 0 for no occurrence. Furthermore, the engineer can assign his given preference (e.g. by function, by process, or by minimised connectivities length) for developing the layout design. The system responds to the preference given by users by assigning different weightings to classes of functions,

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	-	4	8	9	4	8	10	9	9	9	4	4	8	8	8	8	9
1		-	8	9	4	8	10	9	9	9	4	4	8	8	8	8	9
2			-	8	8	8	9	10	9	9	8	8	8	4	4	4	9
3				-	9	9	4	10	4	4	9	9	9	9	9	9	4
4					-	7	9	5	9	9	4	4	8	8	8	8	9
5						-	9	10	9	9	8	8	4	8	8	8	9
6							-	2	2	4	9	9	10	9	9	9	4
7								-	2	5	10	9	10	10	10	10	5
8									-	4	9	9	9	9	9	9	4
9										-	9	9	9	9	9	9	4
10											-	1	7	7	8	8	9
11												-	7	7	8	8	9
12													-	7	8	8	9
13														-	4	4	9
14															-	2	8
15																-	8
16																	-

Activity Unit [0]:Glycol_Contractor1
Activity Unit [1]:Suction_Scrubber2
Activity Unit [2]:Pig_Launcher1
Activity Unit [3]:Pig_Launcher3
Activity Unit [4]:Compressor_Export1
Activity Unit [5]:Compressor_Gas1
Activity Unit [6]:Separator_LP3
Activity Unit [7]:Separator_MP2
Activity Unit [8]:Separator_HP1

Activity Unit [9]:Gas_Drum2
Activity Unit [10]:Cooler_HP2
Activity Unit [11]:Cooler_Export1
Activity Unit [12]:Cooler_After2
Activity Unit [13]:Cooler_Export3
Activity Unit [14]:Pump_Booster2
Activity Unit [15]:Pump_Export2
Activity Unit [16]:Pump_Export1

Fig. 6. The associativity data based on the result of similarity measurement.

processes and connectivities. The system obtains the associativity data by calculating their similarity, using the similarity measure formula (see Table 1 in section 3.3). The result is shown in Fig. 6.

One method which is employed to cluster the equipment after the similarity measurement is *minimised distance* (see Table 1 in section 3.3) for each pair of equipment, as shown in Fig. 7. The items of equipment in the same subprocess will be clustered prior to being grouped by the same function constraint. For example, equipment number 14 and equipment number 15 (the equipment numbers in Fig. 7 correspond to the numbers of the activity units shown in Fig. 6) are in the same subprocess, have similar functions, and are connected together, so they are clustered together. The associativity data produced on the basis of the above described
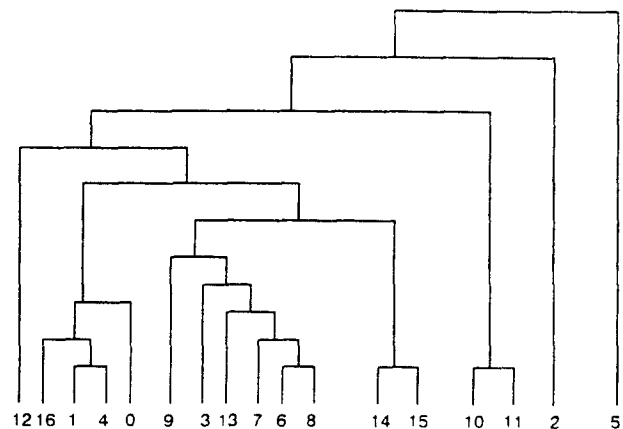

Fig. 7. Minimum distance clustering graph.

rules along with the spatial envelope dimensions of the equipment from the input to the spatial layout design tool. The tool utilises a simulated annealing algorithm for a global search space exploration. Thus the optimised layout produced is in fact the one which best compromises the contradictory requirements described above.

5 FUTURE WORK

The system presented is currently being integrated with an existing PFD system[12] and a simulated annealing layout design system[8] in a distributed environment (the former system is located in the University of Sunderland and the latter one is implemented in the University of Newcastle upon Tyne).

The PFD system incorporates an expert system which extracts relevant information from a PFD design tool. This information is then transformed into a neutral object and transported across the network to the intelligent system responsible for the production of associativity data. This in turn is fed into the simulated annealing algorithms layout design system. The concept of knowledge level[14] associated with ontology[15] will be employed to construct the neutral object. This approach aims at alleviating the difficulties encountered in sharing and reuse of knowledge represented in different languages. Since the system is intended to share knowledge across heterogeneous networks, Common Object Request Broker Architecture (CORBA)[16] will be employed as a transport and standard interface protocol.

6 CONCLUSIONS

To the best of authors' knowledge[17], there has not been an effective approach to the automation of associativity data generation[8]. The system described in this paper incorporates a method for automatically generating associativity data for layout design. In integrates three techniques, namely: expert systems, object-based technology and locational attributes. This resulting system is claimed to be more effective than the current ones. The constraints which affect equipment adjacency are represented in the form of rules. These rules can be reasoned from descriptive information to provide quantitative data, which in turn can lead to the production of associativity data.

The expert system provides a solution to ambiguous requests (e.g. high safety, low cost) from users regarding the selection of equipment. It is also able to select appropriate equipment by referring to the specification implicit in the PFD. The system allows users to spend less effort when producing associativity data. It alleviates the problems of combining subjective and objective factors by providing guidance to layout designers in generating such data.

Regarding a knowledge representation, the major advantage in presenting a PFD in the form of an object-based structure is that it enables it to be processed easily

by computer. This saves time and effort when the need for system expansion arises.

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