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The house of quality in a design process

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The product development process is subject to randomness of duration of design activities and a path followed through the network of activities. In this paper, the qualitative relationships between various attributes of the design process and the corresponding design process variables are captured using the house of quality and then transformed into quantitative relationships. The impact of the process control variables on the design process attributes is discussed. The problem of determining optimal values of the design process variables to maximize the combined quality index of the critical design activities is modelled as a geometric programming problem.

1. Introduction

The product development process has been often performed in isolation from the functional departments contributing to the product realization. This narrow view of the product development process results in costly products that are difficult to produce and often leads to decisions that iterate through different product development stages. With the advent of the concurrent engineering approach, corporations are looking for new ways to restructure and facilitate communication in the design environment. Designers should be able to anticipate and consider constraints and requirements that may occur at the later stages of product development. A design is ultimately evaluated with respect to many different criteria, all contributing to the customer's perception of product quality.

Integrated product and process design is a key aspect of concurrent engineering (CE) (Nevins and Whitney 1989 and Kusiak 1993). One of the objectives of 'concurrent design' is to ensure that serious errors do not go undetected and that the design intent is fully captured. Due to the concurrent consideration of many factors, experts from different functional groups need to contribute towards the design goal. In effect, the design activities are performed by teams with members representing various disciplines. A design team can effectively utilize the concurrent engineering approach only when it works cooperatively and consistently.

The design process consists of several phases ranging from the analysis of customer requirements to manufacturing of the product. Each of these phases can in turn be decomposed into a set of interrelated design activities. The main purpose of this decomposition is to gain control over the total duration of the design process and attain a proper utilization of resources during planning and execution of design activities, so that the total cost is minimized (Pahl and Beitz 1988). Kusiak and Larson (1995) discussed a typology of process representation and decomposition approaches in mechanical design. Activities and their precedences can be represented as a network. It is difficult to control and update a large scale design activity network.

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In addition, it is extremely difficult to consider different types of logical relationships among design activities in a large activity network.

Structured analysis and design technique (SADT) is a graphic language, developed to capture multiple levels of detail in hierarchical manner (see Ross 1977). IDEF encompasses a family of methods, which have been widely used and discussed in the literature. The name IDEF originates from the United States Air Force program for integrated computer-aided manufacturing (ICAM) from which the first ICAM definition, or IDEF, methods emerged. Colquhoun *et al.* (1993) present a detailed review of IDEF0. Hsu (1994) used IDEF0 for modelling manufacturing enterprise. Ang *et al.* (1994) proposed a knowledge-based manufacturing modelling system for the automatic generation of IDEF0 models. Kusiak *et al.* (1994) demonstrated the use of IDEF models for reengineering of design and manufacturing processes.

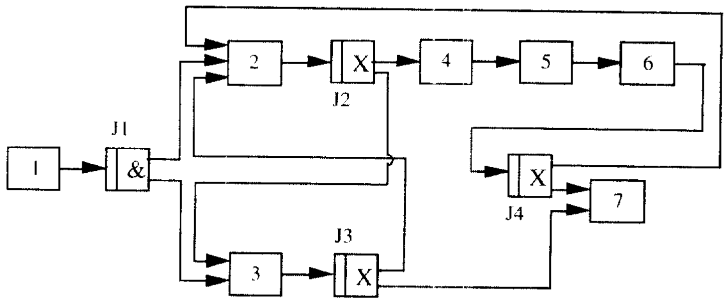
The IDEF3 methodology has been developed to capture a process description (Mayer *et al.* 1992). An IDEF3 model enables an expert to communicate the process flow of a system by defining a sequence of activities and the relationship between them. The IDEF3 methodology uses junctions to describe the logic of a decision making procedure. The effect of the logic is transferred to a lower level decomposition (see Menzel *et al.* 1994). Belhe and Kusiak (1995) presented an approach to resource constrained scheduling in hierarchically structured design activity networks.

In the proposed approach, IDEF3 is used to build an elementary design activity network at the highest level of abstraction. Different types of logical relationships among design activities lead to alternative precedence networks. Some of the activities in a network selected can be further decomposed into lower level activities. The decomposition process can then be recursively applied to the activities at the lower level. When different types of products are handled by the design organization such a representation can be used to build a design activity network that can include all possible activities related to the design process.

The quality function development (QFD) approach enables organizations to translate customer requirements into relevant requirements throughout the design process. The house of quality is a tool for recording and communicating product information to the groups that contribute to the realization of the product (Hauser and Clausing 1988). In the house of quality, only certain design criteria are defined which are important in evaluating the product. These criteria are related qualitatively to the engineering domain and identify the relationship between the customer wants and what engineering must perform to deliver them. The aim of this research is to use the house of quality to assess the performance of the product development process.

In this paper, the house of quality is modified to capture the relationships between design process attributes and control variables (Locascio and Thurston 1994). These qualitative relationships are then transformed into quantitative expressions. The expressions can either be used to examine the effect of change of variable values on the design process attributes or they can be used as constraints to optimize certain quality criteria in the design activity network.

The structure of this paper is as follows. In §2, the IDEF3 representation of a design process is discussed. Section 3 describes the nature of the design process and need for studying qualitative relationships in the design process. In §4, the qualitative relationships between the design process attributes and the corresponding design process variables are discussed. The relationships defined in the house of quality are quantified and a procedure to examine the effect of change in variable values on the



(1) Prepare system specifications
(2) Generate preliminary design
(3) Evaluate cost of different alternatives
(4) Build prototype
(5) Perform tests on prototype
(6) Analyse test data
(7) Finalize design details

Figure 1. Design activity network for design of an electro-mechanical module.

design process attributes is discussed. Section 5 describes the optimization approach to the quality indices of critical design activities.

2. Design activity networks

The precedence networks used in project planning include AND type relationship only. In the precedence network with 'activity on node' (AON) representation, an arc from activity i to activity j means that activity i precedes activity j. Another arc from activity k to activity j means that activity i AND activity k precede activity j. This type of precedences has been used for representing temporal constraints in project networks and other applications. In a design process, different types of logical relationships among design activities may exist. Therefore, a traditional precedence network is inadequate to represent the design process.

The IDEF3 methodology has been developed to capture a process description (Mayer *et al.* 1992). It incorporates the logical relationships of type 'OR', 'EXCLUSIVE OR' (EOR), and 'AND' relationship. Junctions are used to indicate either a split or a merge of two or more paths. The logical relationship among design activities can easily be captured using the IDEF3 representation. When different types of products are handled by the design organization such a representation can be used to build a design activity network that can include all possible activities related to the design process.

The elementary design activity network can be obtained for each of the design phases based on the relationship among these activities. For example, consider design of an electro-mechanical product. The IDEF3 model of the partial design activity network is shown in Fig. 1. The first activity is to prepare system specification from the customer requirements. Once this specification is ready, an activity to generate preliminary design begins which continuously interacts with the activity to evaluate cost of different alternatives. This relationship is shown by the AND junctions, J1 and EOR junctions J2 and J3. Once the preliminary design is ready, a prototype is built and then different tests are performed on this prototype. The type of tests to be performed on this prototype depend on the type of module to be designed. The test data is analysed to confirm the suggested design. If the suggested design is not acceptable, then it needs to be modified. Otherwise, the preliminary design data is used in conjunction with cost estimates to finalize the design details. This relationship is indicated by an EOR junction, J4.

3. Complex nature of the design process

Different types of logical relationships between design activities result in numerous alternative paths through the network. These alternate paths are associated with certain probabilities that may change over time. One cannot exactly predict the path followed through the network or the number of iterations in the design process. The number of iterations depends, for example, on the quality of performing the design tasks and quality of the results of these tasks; however, the quantitative dependence cannot be obtained.

In addition, the number of iterations taking place throughout the design process is not deterministic. This number may largely vary from one project to the other and it may not be possible to collect data and fit a distribution for the duration of different design phases. Also, the nature of the design process changes over time due to new developments in technology, organizational improvements and so on. The duration of some of the design activities may also depend on the availability of resources which itself may change over time. Due to such dynamic nature of the design process, each design project is unique in terms of its time requirements. The quality of the schedule depends on the accuracy with which the activity duration and the set of successor activities is determined. The predictability and standardization found in well planned manufacturing systems is not present to the same degree in the product development process. In design projects, uncertainty and diversity seem to be the predominant features. Therefore, relationships between various design process attributes and variables cannot be captured quantitatively. In this paper, the house of quality is used to qualitatively express these relationships.

4. Relationship between design process attributes and variables

A design process can be represented as an IDEF3 activity network. The management's interest is to improve some characteristics associated with this design process. These characteristics, which the design manager wishes to address but cannot control directly, are the attributes of the design process.

In the house of quality, design criteria are qualitatively related to the engineering domain, identifying the relationships between what the customer wants and what engineering must do to provide it. In this paper, it is proposed that a modified version of the house of quality be used to establish the qualitative relationships between various design process attributes and the corresponding design process variables. In this 'modified' house of quality, design process attributes replace customer attributes and design process variables replace engineering characteristics.

The design process attributes are defined so that they clearly represent the mangement's objectives. Two attributes are combined when each is too specific and their total effect on the design process can be represented by a single goal. An attribute is eliminated if it is not relevant to the goal. An attribute is decomposed into two subattributes, when it can be better represented by two distinct goals. It is required to redefine a design process attribute when it is possible to describe the corresponding goal on a measurable scale.

A number of variables are involved in the design process. The level of these variables can be directly controlled. The exact analytical relationship between these

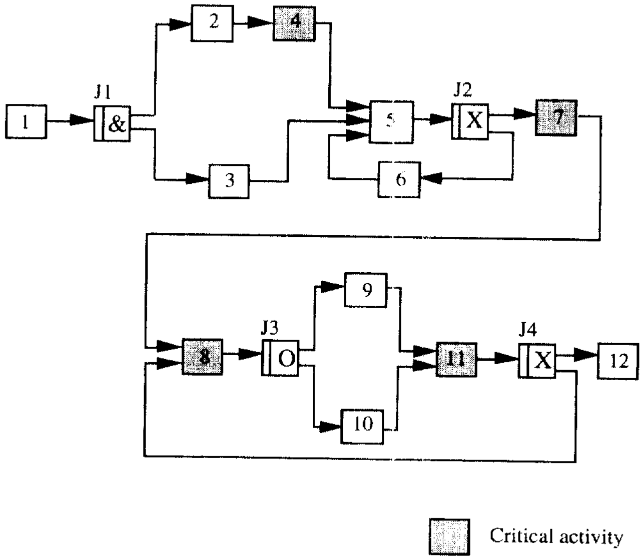


Figure 2. Partial design activity network with critical activities.

No.	Activity
1	Perform project planning
2	Review and analyse customer requirements
3	Develop project coordination document
4	Define design requirements
5	Establish system design goals
6	Perform system tradeoffs
7	Finalize product requirements
8	Develop system requirements
9	Conduct internal requirements review
10	Review requirements with customer
11	Analyse modifications suggested in system specifications
12	Finalize the system specifications

Table 1. List of activities in the design activity network in Fig. 1.

variables and the attributes identified can not be easily established. However, the qualitative impact of each of the design process attributes on the variables can be established. It is assumed that the variables affect the attributes according to the degree of dependency between them. The design process variables selected from the IDEF3 process model may not be independent. Therefore, the interaction between them needs to be considered.

For example, consider the design activity network in Fig. 1. The activities in this network are at a higher level of abstraction. One of the main advantages of using IDEF methodology is that it allows us to decompose an activity at higher level of abstraction into a network of activities at the lower level. The activity 'Prepare specification' in Fig. 1 can be decomposed into a network of activities shown in Fig. 2. The list of activities in Fig. 2 is shown in Table 1.

A design project following the design activity network shown in Fig. 2 may

Relationship matrix	
●	Strong positive
○	Medium positive
▽	Weak positive
×	Negative

Interaction matrix	
○	Positive
×	Negative

Figure 3. Symbols used in the house of quality for design process attributes and variables.

undergo a number of iterations. As a result, the last activity in the network may or may not be completed before the required due date. The design activities have certain resource requirements, without which they cannot be performed. The total number of resources available are limited and that may cause resource conflict between different activities in the design activity network. The duration of design activities is not fixed. It is directly or indirectly influenced by the way design activities are performed. The stochastic duration of design activities affects the length of the critical path. These characteristics of the design activity network are important from the point of view of the management of the design process, however, they cannot be controlled directly. In the approach presented in this paper, the characteristics of the IDEF3 network are treated as design process attributes.

Unlike the design process attributes, the design process variables can be directly controlled. For example, in the design activity network in Fig. 2, the number of resources made available and number of design projects undertaken simultaneously can be controlled. Similarly, the way the design effort is performed, i.e., the level of interaction and concurrency and involvement of different functional groups can also be directly controlled. These control variables have an impact on one or more of the design process attributes. However, the exact quantitative relationships between these design process attributes and the design process variables are not known. Therefore, we use the house of quality to represent these relationships (see Fig. 4) using symbols shown in Fig. 3.

The house of quality in Figure 4 allows us to analyse the relationship between design process variables and design process attributes.

Let n be the total number of attributes. The value of the design process attributes are given by the vector:

$$\boldsymbol{y} = (y_1, y_2, \ldots, y_n)$$

For attribute value y_i, the lower limit and upper limit on its values are denoted by y_{iL} and y_{iU}, respectively. Therefore, the feasible range for y_i is:

$$y_{iL} \leq y_i \leq y_{iU}$$

The design process attributes and their feasible ranges for this example are given in Table 2. These ranges can be obtained from the past data.

Now, let m be the total number of design process variables. Values of the design process variables are given by the vector:

$$\boldsymbol{x} = (x_1, x_2, \ldots, x_m)$$

For variable value x_i, the lower limit and upper limit on its values are indicated by x_{iL} and x_{iU}, respectively. Therefore, the feasible range for x_i is:

$$x_{iL} \leq x_i \leq x_{iU}$$

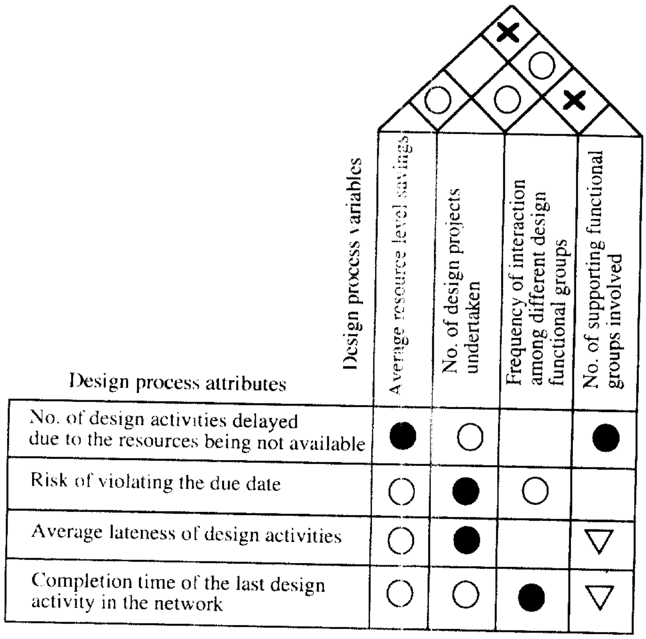


Figure 4. House of quality for a design process.

	Attribute	Range
y_1	No. of design activities delayed due to the resources being not available	$0 \leq y_1 \leq 8$
y_2	Risk of violating the due date	$0 \leq y_2 \leq 1$
y_3	Average lateness of design activities	$2{\cdot}5 \leq y_3 \leq 9{\cdot}4$
y_4	Completion time of the last design activity in the network	$18 \leq y_4 \leq 35$

Table 2. Design process attributes and their feasible ranges.

	Variable	Range
x_1	Average resource level savings	$3{\cdot}2 \leq x_1 \leq 8{\cdot}4$
x_2	Number of design projects undertaken	$4 \leq x_2 \leq 10$
x_3	Frequency of interaction between different design functional groups	$2 \leq x_3 \leq 6$
x_4	Number of supporting functional groups involved	$5 \leq x_4 \leq 10$

Table 3. Design process variables and their feasible ranges.

The design process variables and their feasible ranges for this example are given in Table 3. The design process variables are not required to be independent. The interaction among these variables is shown in the roof of the house of quality in Fig. 4.

The lower and upper limits on the design attributes as well as on the design process variables represent their possible minimum and maximum values, respectively. For example, the risk of violating the due date is the probability with which the due date is

Symbol	Coefficient value
	+9
	+3
	+1
	−3

Table 4. Conversion of symbols.

violated and hence it ranges between 0 and 1. Similarly, in this specific example, there are at least 5 functional groups involved but it is not feasible to include more than 10 functional groups.

Once the ranges on the values of the design process attributes and the design process variables are established, one may want to quantify the relationships between the attributes and variables of this process to examine the effect of increasing or reducing the values of certain design variables on the attribute of interest. The commonly used conversion values for symbols in the house of quality are shown in Table 4.

The value y_i of the design process attribute i, is represented as a function of the design process variables.

$$y_i = f(\boldsymbol{x}) \tag{1}$$

Following the scheme presented in Locascio and Thurston (1994), this functional relationship includes first order effects from the relationship matrix and second order effects from interaction matrix. The design process variables are scaled on to the range of 0 to 1 to obtain the vector of relative design process variable values:

$$\boldsymbol{x}' = (x'_1, x'_2, \dots, x'_m)$$

When the values of the relative design process variables, x', are used in place of the original process variable values, x, in equation (1), the relative design process attribute values are obtained:

$$y'_i = f(\boldsymbol{x}') \tag{2}$$

This transformation from original values to the relative values is done to capture the impact of variables on attributes from the house of quality. The use of these relationships is discussed next.

The functional relationship between design process attributes and design process variables can be further expressed by considering the conversion of symbols in Table 4. For example, the expression for the scaled attribute y'_2 corresponding to 'Risk of violating the due date' is written as:

$$y'_2 = 3x'_1 + 9x'_2 + 3x'_3 + 3x'_1x'_2 + 3x'_2x'_3 \tag{3}$$

Similarly, the expressions for the remaining relative attributes are given by:

$$y'_1 = 9x'_1 + 3x'_2 + 9x'_4 + 3x'_1x'_2 - 3x'_1x'_4 \tag{4}$$

$$y'_3 = 3x'_1 + 9x'_2 + x'_4 + 3x'_1x'_2 - 3x'_1x'_4 \tag{5}$$

$$\begin{aligned} y'_4 = {} & 3x'_1 + 3x'_2 + 9x'_3 + x'_4 + 3x'_1x'_2 + 3x'_2x'_3 \\ & - 3x'_1x'_4 + 3x'_2x'_4 - 3x'_3x'_4 \end{aligned} \tag{6}$$

Design variable	Old value x_i	Old value x'_i	New value x_i	New value x'_i
Average resource level savings	5·6	0·46	6·8	0·69
Number of design projects undertaken	6	0·33	6	0·33
Frequency of interaction between different design functional groups	3	0·25	5	0·75
Number of supporting functional groups involved	8	0·6	8	0·6

Table 5. The values of design process variables.

The allowable range for each relative design process variable is [0, 1]. The allowable range for the relative design process attribute is computed by minimizing and maximizing the expressions for the relative design process attributes.

When one wants to determine the attribute value corresponding to a specific combination of values assigned to the design process variables, the values of the relative design process variables are determined first. Then the value of the relative design process attribute is determined using the expression in terms relative design process variables. This value is then mapped back on to the original range of the design process attribute to obtain the actual value of the design process attribute.

For example, reconsider y'_2 corresponding to 'Risk of violating the due date'. The minimum (maximum) values of y'_2 is obtained by minimizing (maximizing) expression (3). The minimum (maximum) value of y'_2 obtained is 0 (21).

Therefore, the expression for y_2 is:

$$y_2 = 0 + ((1 - 0)(3x'_1 + 9x'_2 + 3x'_3 + 3x'_1x'_2 + 3x'_2x'_3)/21) \tag{7}$$

Suppose that one is interested in assessing the change in 'Risk of violating the due date' when values of design process variables changed to a new set of values. The old values for the set of design process variables and the corresponding new values are given in Table 5.

The value of y_2 is determined from equation (7). Initially, the value of y_2 is 0·28 and after increasing the value of variables 'Average resource level savings' and 'Frequency of interaction between different functional groups' (see Table 5), the new value of y_2 is 0·42.

Similar to equation (7), equations for other design process attributes are obtained:

$$y_1 = (8 - 0)(9x'_1 + 3x'_2 + 9x'_4 + 3x'_1x'_2 - 3x'_1x'_4)/21 \tag{8}$$

$$y_3 = 2{\cdot}5 + (9{\cdot}4 - 2{\cdot}5)(3x'_1 + 9x'_2 + x'_4 + 3x'_1x'_2 - 3x'_1x'_4)/13 \tag{9}$$

$$\begin{aligned} y_4 = 18 + (35 - 18)(3x'_1 + 3x'_2 + 9x'_3 + x'_4 + 3x'_1x'_2 + 3x'_2x'_3 \\ - 3x'_1x'_4 + 3x'_2x'_4 - 3x'_3x'_4)/19 \end{aligned} \tag{10}$$

In this way the impact of a change in any variable value on the values of design process attributes can be studied by deriving quantitative relationships from the house of quality for the design process. Based on these relationships, any desired changes in the values of design process attributes can be implemented by making appropriate changes in the design process variables.

	Activity no.	Critical activity name	Limits on quality index
y_1	4	Define derived requirements	$0 \leq y_1 \leq 1$
y_2	7	Finalize product requirements	$0 \leq y_2 \leq 1$
y_3	8	Develop system requirements	$0 \leq y_3 \leq 1$
y_4	11	Analyse modifications suggested in system specifications	$0 \leq y_4 \leq 1$

Table 6. Critical design activities used as design process attributes and their feasible ranges.

	Variable	Limits
x_1	Average level of expertise	$0 \leq x_1 \leq 8$
x_2	Average resource level	$4{\cdot}6 \leq x_2 \leq 12{\cdot}34$
x_3	Frequency of interaction between different functional groups	$1 \leq x_3 \leq 5$
x_4	Number of resource preemptions	$8 \leq x_4 \leq 25$
x_5	Number of information sources	$3 \leq x_5 \leq 11$

Table 7. Variables affecting the quality of design activities and their limits.

5. Optimizing the quality of performing critical design activities

The quality of results of design activities depends upon the quality of performing these activities. A design engineer may select activities that are critical to the quality of the design. For example, in the design activity network, shown in Fig. 2, activities 4, 7, 8, and 11 are critical.

In this section, we analyse the relationship between the quality of performance of critical design activities and the design process control variables. In the house of quality, the critical design activities replace the design process attributes and the corresponding design process variables are determined. In order to measure the quality of the critical design activities, quality indices are used. The quality index for each design activity is in the range of 0 to 1, where 1 corresponds to the best quality and 0 corresponds to the lowest quality. The design process attributes y_1, y_2, y_3, and y_4 and the corresponding ranges are shown in Table 6.

The set of design process variables include two of the previously defined variables, 'frequency of interaction between different functional groups' and 'average resource level'. In addition, 'level of expertise' is used as a design process variable. This variable refers to the average experience of a designer in terms of number of similar projects handled in the past. Since the designers are also assigned other responsibilities and these may affect the quality of input from the team member, 'number of resource preemptions' is used as a variable. The information required by the designer may become available from a variety of sources. The designer may try to minimize the risk of using wrong information by referring to more than one source of information so that he/she can verify the information obtained from other sources. Therefore, 'number of information sources' is treated as a variable affecting quality of performance of certain design activities. The variables and the corresponding limits are listed in Table 7.

The next step is to construct the relationship matrix and the interaction matrix for the relationships between the quality indices of the critical design activities and the corresponding design process variables. The house of quality is shown in Fig. 5.

As discussed in § 4, expressions for each of the attributes in terms of the process

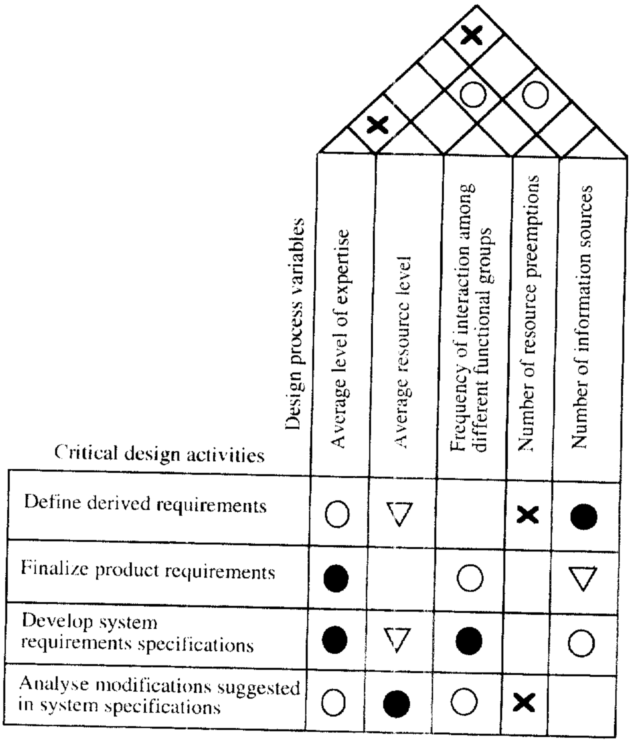


Figure 5. The house of quality for relationships between critical activities and process variables.

variables and their interaction are developed. The values of the design process variables are scaled to [0, 1]. Then the procedure discussed in §4 is used to obtain the quality indices for each critical design activity in terms of the relative design process variables. These expressions are as follows:

$$y_1 = 0 + ((1-0)(3x'_1 + x'_2 - x'_4 + 9x'_5 - x'_1x'_2 - x'_1x'_5 + 3x'_2x'_4/13) \qquad (11)$$

$$y_2 = 0 + ((1-0)(9x'_1 + 3x'_3 + x'_5 - x'_1x'_5 + 3x'_3x'_5)/13) \qquad (12)$$

$$y_3 = 0 + ((1-0)(9x'_1 + x'_2 + 9x'_3 + 3x'_5 - x'_1x'_2 - x'_1x'_5 + 3x'_3x'_5)/17) \qquad (13)$$

$$y_4 = 0 + ((1-0)(3x'_1 + 9x'_2 + 3x'_3 - x'_4 - x'_1x'_2 + 3x'_2x'_4)/16) \qquad (14)$$

Assume that $w_i, i = 1, 2, 3, 4$ are the weights assigned to four critical design activities listed in Table 6. These weights are assigned to the critical design activities. Our goal is to determine the values of design process variables to maximize the combination of the quality indices of the critical activities. The optimization problem can be modelled as follows:

$$\begin{aligned} \text{Maximize} \quad & w_1y_1 + w_2y_2 + w_3y_3 + w_4y_4 \\ \text{s.t.} \quad & (11)-(14) \\ & 0 \le x'_i \le 1 \qquad \text{for } i = 1, 2, 3, 4 \end{aligned} \qquad (15)$$

The objective function (15) is the weighted sum of the quality indices of the critical design activities. The expressions (11)–(14) form the constraints for the problem, where the relative design process variables used in these expressions have a range [0, 1]. The constraints (11)–(14) can be substituted to the objective function. The

	Variable	Best value	Alternate value
x_1	Average level of expertise	6	6
x_2	Average resource level	11	9
x_3	Frequency of interaction between different functional groups	4	4
x_4	Number of resource preemptions	10	10
x_5	Number of information sources	9	7
Value of the objective function		68·1	59·33

Table 8. The values of variables affecting the quality of critical design activities.

resulting constrained geometric programming problem can then be solved using standard techniques. The optimal solution to this problem are the values for the relative design process variables $x'_i, i = 1, 2, 3, 4$. These values can be mapped back on to their original ranges.

For example,

$$w_1 = 10, \quad w_2 = 35, \quad w_3 = 20, \quad w_4 = 15$$

The resulting problem is:

$$\begin{aligned} \text{Maximize} \quad & 10y_1 + 35y_2 + 20y_3 + 15y_4 \\ \text{s.t.} \quad & (11) - (14) \\ & 0 \le x'_i \le 1 \quad \text{for } i = 1, 2, 3, 4 \end{aligned}$$

Substituting (11)–(14) to the objective function we obtain:

$$\begin{aligned} \text{Maximize} \quad & 39{\cdot}94x'_1 + 10{\cdot}38x'_2 + 21{\cdot}47x'_3 - 1{\cdot}71x'_4 + 13{\cdot}74x'_5 \\ & -2{\cdot}88x'_1x'_2 - 4{\cdot}63x'_1x'_5 + 5{\cdot}12x'_2x'_4 + 11{\cdot}6x'_2x'_5 \end{aligned} \tag{16}$$

$$\text{s.t.} \quad 0 \le x'_i \le 1 \quad \text{for } i = 1, 2, 3, 4 \tag{17}$$

The problem (16)–(17) is a signomial geometric programming problem (see Beightler 1976 for further details).

The optimal solution obtained to this problem is:

$$x'_1 = 0{\cdot}75, \quad x'_2 = 0{\cdot}93, \quad x'_3 = 0{\cdot}832,$$

$$x'_4 = 0{\cdot}1, \quad x'_5 = 0{\cdot}95$$

These values of the relative design process variables are then mapped on to their original ranges to obtain the best values for control variables as shown in Table 8.

The best set of values for the design process variables shown in Fig. 5 indicate that for a fairly high quality performance of design activities, we need a very good amount of expertise, high resource level, good frequency of interaction among functional groups, small resource preemptions, and a very high number of information sources. The value of the objective function in (16) is indicative of the overall quality of performance of critical activities. As shown in Table 8, if we slightly reduce the values of variables 'Average resource level' (from 11 to 9) and 'Number of information sources' (from 9 to 7), then the value of the objective function reduces from 68·1 to 59·33 (by almost 13%). In this way, optimal values of the design process variables corresponding to a function of design process attributes, with a given set of qualitative relationships between them represented by the house of quality, are determined. This approach also further helps to determine the impact of change in values of design process variables involved on the overall quality of the performance of critical design activities.

6. Conclusion

In this paper, the relationships among design process attributes and variables were studied. The design process was represented with an IDEF3 model. Due to the randomness involved in the design process, qualitative relationships between design process attributes and the corresponding variables were established. These relationships were represented by the house of quality, and then transformed into quantitative relationships. It was shown that such quantitative relationships could be used to study the impact of the design process variable on the design process attributes. The use of these quantitative relationships as constraints in maximization of the desired function of the process attributes was discussed.

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