Optimization Models for Quality Function Deployment in Emergency Planning and Management

Dr. Suleyman Tufekci
Department of Industrial and Systems Engineering
University of Florida
Gainesville, FL 32611

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ABSTRACT

In the last 10 years, an engineering tool, Quality Function Deployment (QFD) has gained a wide acceptance for organizing and ranking information into matrix form in order to understand the attributes or actions that are needed to achieve a common goal, and to align cross-functional teams strategically to quickly and efficiently meet that common goal. Although this tool has been used primarily in the manufacturing world, for product or process planning, recently it is finding its way at various service organizations as well as within the emergency planning and emergency response environment as an aid to prioritize critical resources. In this paper, we will discuss the models that can be used for improving the quality of service for emergency management by using QFD and optimization at local, state and federal levels. By utilizing QFD, these entities will be better able to address emergency situations. Utilization of limited resources for maximum benefit to society in emergency management can be performed successfully with the QFD models combined with optimization techniques.

1. INTRODUCTION

Applying the Quality Function Deployment (QFD) methodology to assist emergency managers (EM) in organizational planning and decision making before, during and after emergencies has been suggested by Schaub and Tufekci [9]. In this approach, by using the model of House of Quality (HoQ), the EM team organizes and ranks information into matrix form in order to understand the attributes or actions that are needed to achieve a common goal of providing a good planning and response to help mitigate disasters.

QFD was one of the tools that was developed in Japan in order to take into account the expertise of various management roles throughout a company, and use that expertise to prioritize improvement efforts. In the mid-1980's, US companies such as Ford Motor Co., IBM, Hewlett-Packard and Allied-Signal Aerospace, have adopted the QFD methodology to strategically plan for improvement projects, product mix decisions, service issues, and product development.

This paper builds upon our previous paper [9]. Here, we will illustrate how QFD can be used in conjunction with optimization models to allocate limited resources available for emergency management for maximum utility to the public. We review the HoQ built for emergency management operations specifically suggested for emergency management and response due to hurricanes but it can be adopted to other emergencies with similar ease.

The models developed in this paper show applications for use at the individual user level, at the local response level and at state and federal levels for hurricane preparedness in the state of Florida, but are general enough to show how QFD can be used in other emergency planning in other locations and with other scenarios.

2. A HoQ FOR HURRICANE EMERGENCY MANAGEMENT

A typical HoQ which was suggested in [9] for hurricane emergencies is given in Figure 1. In manufacturing area, the HoQ matrices are created sequentially, The first matrix usually is a high level overview, succeeding matrices are a flow-down of more detail, possibly focusing only on one sub-topic each. Each HoQ matrix at a given level is intimately related to its preceding and succeeding matrices. This relationship will be made clear in later sections.

2.1 Components of a HoQ

The left side of the matrix consists of a list of "what's", sometimes also referred to as the customers' needs. In the original uses of QFD, this is a list of customers' expectations. For emergency planning purposes, this will be a list of "what's" the public needs to be done in pre-disaster, during or post-disaster. A variation on this part of the matrix is to create a primary, secondary and even tertiary lists that get further and further into specific detail.

Across the top of the matrix is the list of "how's". This list is created after the "what's" and should be done separately. In manufacturing, these "how's" are also termed as technical specifications, quality characteristics or product specifications. They are the technical specifications of the designed product or service which will address the customers' needs. In the case of an emergency management application, types and characteristics of response teams, communication equipment, computer hardware and software, action plans, etc. may be a part of this "how's" list.

In the next stage, the HoQ matrix is filled in by looking at each "how" and determining how much a particular "how" addresses a particular "what". A very strong relationship is given a value of 6. A strong relationship is given a value of 3, and a weak relationship, a value of 1. In the case of no relationship between a what and a how, the square is left blank, and has a corresponding value of 0.

It is also important to assess the importance of each "what" as perceived by the public. This assessment is usually done via questionnaires or interviews with the public. A column is placed just next to the list of "what's" (the tertiary or final list) that ranks the importance of carrying out each item. These ratings are given a rank of:

5 = mandatory
4 = necessary
3 = desirable
2 = minor
1 = minimal

The correlation matrix, located above the "how's", is known as the roof of the house. This part of the QFD chart uses symbols to define the relationship matrix, and determines the strength of the technical interrelationship between each of the "how's". A strong positive relationship is designated by a solid circle, a positive relationship is designated by an open circle, a negative relationship is an "x", and a strong negative relationship is a "double x". The roof becomes important during the resource allocation phase of QFD. Because of these correlation between the "how's", altering the specifications on one "how" may influence the effects of other "how's". Therefore, in performing "what if" analyses on the design of the emergency management system, these correlation are referenced frequently.

2.2 Prioritizing the Information

For a given "how" column, by summing each "what" importance value multiplied by the values in the relationship matrix we get a measure providing us with how significant this "how" is in terms of satisfying the public's needs. The higher this sum is, the more desirable the "how" is in satisfying the public's needs.

The final part of the basic QFD chart consists of an evaluation of "how well" each of the "what's" is currently being executed. For disaster planning purposes this can be a ranking of how well that particular need was satisfied with the current system in effect. In this section we can also evaluate other EM agencies in terms of their effectiveness for answering similar "what's". This, in turn, becomes a benchmarking tool for comparing one's EM services with the others. Such evaluations and comparisons help establish areas where customers' needs are satisfied successfully and also the areas where improvement is needed to bring the services to acceptable levels.

3. USING QFD FOR EMERGENCY PLANNING

The following list as given in [9] provides input for the first level QFD matrices for local, state and federal emergency management efforts. In each case we list the potential "what's" for the agency followed by the "how's". Naturally, if desired, in the next level of QFD matrices, we may list the "how's" of the first level as "what's" of the second level, in a cascading manner. We must then develop the necessary "how's" corresponding to these new "what's" at level two. This hierarchical decomposition of "how's" and "what's" may be continued to the level of detail needed by the specific agency.

What's for Local Government

- Provide timely and accurate storm information
- Provide adequate safety
- Provide rapid mitigation efforts
- Provide adequate shelters
- Provide adequate guidance
- Provide basic needs
- Provide outside communication

What's for State Government

- Provide timely and accurate storm information
- Provide adequate safety
- Provide rapid mitigation efforts
- Provide adequate shelters
- Provide adequate guidance
- Provide basic needs
- Provide outside communication
- Provide resources for preparedness
- Provide resources for education and training

What's for Federal Government

- Provide quick federal presence
- Provide resources for mitigation efforts
- Provide resources for preparedness
- Provide resources for training and education
- Provide communication facilities for the public
- Provide safety for public
- Provide logistic and material support to local and state emergency personnel.

Similarly, the "How's" at each level are listed as

<u>How's for Local Government</u>

- Accurate tracking of storm
- Accurate estimate of landfall consequences
- Accurate estimate of resource needs prior to a landfall
- Accurate estimate of resource needs during the hurricane landfall
- Accurate estimate of resources needed after the hurricane
- Population/crowd control before, during and after the hurricane
- Resource management and allocation
- Traffic control for better evacuation
- Shelter management for optimal shelter utilization
- Provision of basic services for sheltered people
- Provision of postal and telecommunication facilities for the residents

<u>How's for State Government</u>

- Provide state resources for storm tracking
- Provide resources for safety and traffic control
- Provide communication equipment
- Provide shelters
- Provide resources for rapid damage and needs assessments
- Coordinate with local authorities
- Coordination with federal authorities
- Provide visible state government presence
- Provide basic services
- Provide financial assistance to the community
- Provide funds for education/training
- Provide communication facilities for the public

<u>How's for Federal Government</u>

- Provide resources for storm tracking
- Provide FEMA support
- Provide military support
- Provide National Guard support
- Provide financial support
- Provide communication equipment
- Provide postal service
- Coordinate with local EM agencies
- Coordinate with state EM agencies
- Provide funds for clean up and rebuilding
- Provide funds for training and education
- Provide funds for research

In Figure 1, the QFD matrix including local, state and federal agencies "how's" to public's needs is provided. We did not include the "roof" correlation part of the matrix. From the relative importance of each "what" and each "how" the QFD, each EM agency needs to give priority to its resource management and allocation issues. These priorities are indicated by having the highest rank on the list of "how's" for that EM agency.

4. OPTIMIZATION MODELS FOR THE ESTABLISHMENT OF TARGET VALUES FOR "HOW'S"

Each "how" listed in the matrix can be accomplished in more than one way. For example, providing postal and telephone services for the residents after a disaster may be accomplished by having one telecommunications facility including mail and phone services or several facilities with mail, standard telephone and wireless telephone capabilities. Of course, depending upon the services provided, the public's perception and satisfaction will vary. Note that through questionnaires and interviews, the EM team will already have the satisfaction of public on each "what" based on current "how's" already available. Therefore, if we let y_i represent the public satisfaction level of the ith "what" based on current levels of each "how" which is represented by a symbol x_j, then the relationship between each y_i and the decision variables x_j , j=1,2,..,n is a function

$$y_i = f(x_1, x_2, \ldots, x_n), \quad i=1,2,\ldots,m. \tag{1}$$

Furthermore, due to correlation between "how's", the target value of the jth "how" is affected by the target values of the other "how's" it is correlated to. This functional relationship between "how" j and other "how's" is expressed by a function

$$x_j = g_j(x_1, x_2, \ldots, x_{j-1}, x_{j+1}, \ldots x_n) \tag{2}$$

The decision problem is then to choose the right levels of x_j's (within the limits of available resources) such that the public's satisfaction is maximized while Equations (1) and (2) are satisfied.

The next issue in developing the optimization model is an expression for an appropriate function for public's satisfaction. This can be accomplished by using a multiattribute value (MAV) function as suggested by Kim, Moskowitz, Dhingra and Evans [8]. This MAV function $V(y_1,y_2,\ldots,y_m)$ can be additive, multiplicative or nonlinear. The most commonly used form is the additive model. This model expresses the value function of the public as

$$V(y_1,y_2,\ldots,y_m) = \Sigma\, w_i V_i(y_i) \tag{3}$$

where $V_i(y_i)$ is the utility function of the public with respect to "what" i and w_i are the scaling constants such that $0 < w_i \leq 1$, and $w_1+w_2+\ldots+w_m = 1$. The individual utility functions $V_i(y_i)$ are established by acquiring the proper input from the public such that V_i(least favorable y_i) = 0 and V_i(most favorable y_i) = 1. In terms of utility theory, the type of function selected defines the risk aversion profile of the person providing the input. If one uses nonlinear function then the corresponding optimization problem becomes a nonlinear optimization problem. If one selects a linear utility function the resultant objective function becomes a linear function. Finally, each level of "how" selected requires certain amount of resources to be committed by the related agency. Assuming that the resources are limited, the problem then becomes of allocating the right amount of resources to all "how's" so that the resource budget is not exceeded and the public's MAV function is maximized.

The complete optimization then becomes

$$\text{maximize} \quad V(y_1,y_2,\ldots,y_m) = \Sigma\, w_i V_i(y_i)$$

subject to,

$$yi = f_i(x_1,x_2,\ \ldots,\ x_n), \qquad i=1,2,\ldots,m,$$

$$x_j = g_j(x_1,x_2,\ldots,x_{j-1},x_{j+1},\ldots x_n), \qquad 1,2,\ldots,n,$$

$$h_k(x_1,x_2,\ldots.x_n) \leq \ R_k, \qquad k=1,2,..,q,$$

$$y_j \geq 0,\ j=1,2,\ldots,m, \quad x_i \geq 0, \quad i = 1,2,\ldots,n.$$

Here, $h_k(x_1,x_2,\ldots,x_j,x_{j+1},\ldots x_n)$, is the resource consumption function representing the total amount of resource k needed for providing a service whose target values for each "how" j is set at x_j. Note here that for some "how's", the selection may only be between a few discrete possibilities. In this case, the optimization problem becomes one of either all integer or mixed integer optimization problem. As an example, consider the number of storm shelters to open before a hurricane landfall. The decision variable x_j, in this case is the number of shelters to open for public. Clearly, this is a discrete decision variable and each opened shelter will require manpower and additional material resources to operate. Similarly, the satisfaction of public on safety will be a function of the allocation of local law enforcement personnel to various tasks. Therefore, the decision variable of the number of law enforcement personnel assigned to shelters, traffic control and patrolling the evacuated neighborhoods is also a discrete variable.

It is not uncommon in literature to see linear models used for decision making. For example, assuming linear utility function for public (implying risk neutrality), linear additive models for f_i, g_i, and h_i, yields a linear optimization problem possibly with integer variables. Although integer version of the linear problems are harder to solve, if justifiable, solving the linear versions and rounding to nearest integer values may provide reasonable solutions to deal with the decision problem at hand.

In establishing the functions f_i and g_i, crisp linear regression or fuzzy regression using the available data are suggested [8]. In the crisp regression model, the linear regression is performed between current levels of "how's" and the customer satisfaction y_i. That is the coefficients a_{ij}, i=1,2,..., m, j=1,2,..., n are established in

$$
\begin{aligned}
y_1 &= a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n \\
&\;\;\vdots \\
y_m &= a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n
\end{aligned}
\qquad (4)
$$

with least square linear regression model using current levels of "how's" and the acquired public's satisfaction levels y_j's.

Once the a_{ij} values are estimated, they are then used in the optimization model where y_j's and x_i's are the decision variables.

5. CONCLUSIONS

In this paper we have shown how QFD can be used in the field of emergency management. We have provided a general optimization model that can be used in conjunction with the QFD. The proposed optimization models help EM agencies to allocate resources to all the "how's" in such a way that the public's satisfaction is maximized.

QFD provides a means of acquiring public's needs. Furthermore, it helps EM agencies to determine their weaknesses and strengths. It allows agencies to systematically improve their services by allocating their limited resources to EM efforts in an optimal manner with the total public's satisfaction as the driving force.

There is more that needs to be done before QFD methodology becomes an integral part of EM field. Studies are needed to establish public's utility functions for each "what" that is the expression of public's needs. Furthermore, more research needs to be done in establishing classes of functions for fi, which appropriately represent the functional relationships between "how's" and the particular need as defined as "what" i. Finally, the functional relationships g_i, between the "how's" need to be researched extensively. Probably, the development of the resource consumption functions h_i is the easiest one to handle. It may not be as difficult to estimate resource requirements of each "how " j for a desired target level x_j.

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