Development of an Exportable Modular Building System by Integrating Quality Function Deployment and TRIZ Method

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Abstract
Quality function deployment and TRIZ method are widely used to develop new products in the manufacturing industry. These methods are known to be extremely effective for cost reduction and quality improvement. However, unlike the general manufacturing process, the manufacturing of an exportable modular building system involves many sub-processes that proceed concurrently. Therefore, there is a limitation on the efficiency that can be achieved if either of these methods is directly applied to product development. In order to address this issue, the authors propose a new methodology wherein quality function deployment is integrated into TRIZ. The results of a case study show that application of the new method makes it possible to reduce the volume of an exportable modular building system compatible with ISO container shipping by 48% and to decrease the weight of structural steel by 30%.

Keywords: TRIZ; quality function development; integration; exportable modular building system

1. Introduction
Quality function deployment (QFD) is a customer-driven methodology in which customers’ needs are systematically transformed into product specifications (Kim et al., 2015). Generally, QFD is applicable over a number of phases. The first phase is to derive the critical to quality (CTQ) through a correlation analysis between quality characteristics and the customers' needs. In the second phase, the key functions are determined through correlation between the quality characteristics and required functions. In the final phase, the product is designed through a correlation analysis between the functions and design factors. This methodology is widely used in the manufacturing (Akao, 1994) and construction industry (Pheng and Hui, 2004, Chun and Cho, 2015).

TRIZ (a Russian acronym for the theory of inventive problem solving) is an effective methodology to derive creative ideas on new product development; it was proposed by Altshuller et al. (2002) and the core concept of TRIZ is the resolving of contradictions. A number of technical inconsistencies and physical contradictions may arise during the application of QFD. For example, 'I' and 'II' are both important quality characteristics that reflect the customers' needs. It may happen that if the quality of 'I' increases, then that of 'II' decreases, and vice versa; thus, it may be difficult to satisfy the requirements for both 'I' and 'II' simultaneously. In order to solve this problem, several researchers developed a new methodology in which QFD is integrated into TRIZ to resolve the technical contradictions. This idea has been applied to the development of manufacturing products; examples of this method applied to the manufacture of a laptop computer and a washing machine are discussed by Yeh et al. (2011), and Yamashina et al. (2002), respectively.

In this study, the authors developed an exportable modular building system using a new methodology, which integrates TRIZ and two phases of QFDs. An exportable modular building system is a good option for situations in which the supply of sufficient labor and materials to foreign construction sites is difficult (Eom et al., 2014, Lawson et al., 2011). In general, owing to the large volume of exportable modules, the delivery cost of such systems makes up approximately 30% of the total cost. Hence, it is important to develop a system that will incur low delivery cost. The integrated TRIZ-QFD methodology was used to find a balance between the small volume and high manufacturing cost of the exportable modules.

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(Received October 1, 2016 ; accepted July 12, 2017)
DOI http://doi.org/10.3130/jaabe.16.535
2. Integration of TRIZ and Two-phases of QFD

When applying QFD methodology, the house of quality (HOQ) structure is used to convert the quality required by customers into the quality characteristics for design of products (Akao, 1994). Fig.1. shows two HOQs that represent the first and second phases of the QFD analysis, respectively. The first phase of the QFD methodology is usually applied to perform a correlation analysis between quality requirements and characteristics. If a physical contradiction arises in the correlation of quality characteristics represented by room A of Fig.1.(a), TRIZ is used in this step.

Fig.1.(b) shows the second phase of QFD methodology. Based on the results of the first phase of QFD analysis, quality characteristics are rated, and CTQs are chosen. In the second phase of QFD, a correlation analysis between quality characteristics (Room 3 of Fig.1.(a)) and function requirements (Room 6 of Fig.1.(b)) is performed. TRIZ can be repeated to resolve physical contradictions among the function requirements. Based on the results of the second phase QFD analysis, the function requirements are rated, and the key functions are determined.

A new procedure is proposed, as shown in Fig.2.; it involves integrating two phases of QFD and TRIZ and is called a functional HOQ (F-HOQ). In this procedure, rooms 6, 7, 8, and B of the second phase of the QFD are attached to the first phase of the QFD. By integrating these two phases, all the quality requirements (QRs), quality characteristics (QCs), and function requirements (FRs) can be directly related in a single diagram. Rooms A and B in the figure represent the correlations among the QCs and FRs, respectively. This diagram shows their contradictions, and thus, TRIZ can be easily applied in a single diagram.

3. Case Study of Integrated QFD and TRIZ

The developed F-HOQ was applied to the design of a representative example of exportable modular accommodation modules for construction workers. The plan view and shipped modules are shown in Fig.3.

3.1 Determination of CTQs

To derive the quality requirements, customers’ opinions were obtained by surveying and interviewing potential customers; the opinions were converted into quality requirements. The obtained quality requirements are grouped into three levels as listed in Table 1.
As presented in Table 2., critical customer requirements (CCRs) and CTQs can be determined through an analysis process corresponding to rooms 1 to 5 of F-HOQ. Through the correlation analysis between QRs and QCs, the priorities of the QCs can be evaluated. The quality requirements of level 3 are rearranged into room 1 in the F-HOQ. The QCs are assigned different weights, such as ◎: 5 points, ○: 3 points, and △: 1 point, depending on their relation with the corresponding customer requirements. Among the five QCs, the top three are selected as CTQs and used to set up development targets. Table 3. lists the top three CTQs and their target levels.

Table 1. Quality Requirements Grouped into Three Levels

| Level 1 | Level 2 | Level 3 |
|---------|---------|---------|
| Easy to deliver | Easy to export modules | Compatible with ISO container ships |
| Low shipping cost | A small amount of site work | A small number of components |
| Easy to construct | Low manufacturing cost | Low manufacturing cost |
| Excellent residential performance | Good to use | Large space inside modules |
| High structural performance | Small deflection under loads | |

Table 2. Rating Quality Requirements and Quality Characteristics Corresponding to Rooms 1, 2, 3, 4, and 5 of F-HOQ

| Quality characteristic | Quality requirement | Volume of delivery | Weight of frames per unit area | Number of components per unit volume | Number of components per unit volume | Ratio of ceiling height and module height | Maximum beam deflection | 1) Importance rating | 2) Satisfactory rating | 3) Possible quality level | 4) Level up ratio | 5) Sales Point | 6) Absolute priority | Rating |
|-----------------------|---------------------|-------------------|-----------------------------|-------------------------------------|-------------------------------------|------------------------------------------|-----------------------------|---------------------|---------------------|----------------------|----------------|----------------|----------------|--------|
| Compatible with ISO container ships | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | 5 | 4.4 | 2 | 1 | 0.5 | 2.2 | 2.94 | 5 | 37.50 | 50.09 | 1 |
| Low shipping cost | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | 4.6 | 2.6 | 1 | 0.4 | 1.77 | 2.36 | 5 | 621 | 245 | 97 |
| Small number of components | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | 5.9 | 2.37 | 2.8 | 8.4 | 5.2 | 4.6 | 2.6 | 1 | 0.4 | 1.77 | 2.36 | 5 |
| Low manufacturing cost | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | 5.9 | 2.37 | 2.8 | 8.4 | 5.2 | 4.6 | 2.6 | 1 | 0.4 | 1.77 | 2.36 | 5 |
| Large space inside modules | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | 5.9 | 2.37 | 2.8 | 8.4 | 5.2 | 4.6 | 2.6 | 1 | 0.4 | 1.77 | 2.36 | 5 |
| Small deflection under loads | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | 5.9 | 2.37 | 2.8 | 8.4 | 5.2 | 4.6 | 2.6 | 1 | 0.4 | 1.77 | 2.36 | 5 |
| Absolute priority | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | ◎ | 5.9 | 2.37 | 2.8 | 8.4 | 5.2 | 4.6 | 2.6 | 1 | 0.4 | 1.77 | 2.36 | 5 |

Table 3. Definitions and Target Levels of CTQs

| CTQ | Management definition | Current level | Target level |
|-----|-----------------------|---------------|--------------|
| Volume of modules for delivery | Volume of entire building units for delivery | 1197.74 m³ | 598.87 m³ |
| Weight of frames per unit area | Weight of steel frames per unit area | 0.59 kN/m² | 0.53 kN/m² |
| Ratio of ceiling height and module height | Proportion of inner height to outer height of the module (except the depth of beam and finishing thickness) | 0.85 | 0.85 |

Fig.4. Function Analysis of the Exportable Modular Building
3.2 Determination of Key Functions

After determining the CTQs through the correlation analysis, the key functions of the exportable modular building were derived. Fig. 4 illustrates the process of the function analysis of the exportable modular building. The functions in Fig. 4 correspond to room 6 of F-HOQ. The key functions are derived from a correlation analysis between the QCs and required functions. Room 8 of F-HOQ shows the priority ratios of the key functions. Among the functions considered in Fig. 4, "Shipping," "form of modules," and "form outside the module" were finally selected as the key functions. This procedure is illustrated in Table 4.

3.3 Integration of TRIZ and QFD

Effective solutions can be obtained by resolving technical problems with contradictions. The contradictions generally occur if the improvement of a parameter or a characteristic of a technical system causes the deterioration of other parameters or characteristics. The contradiction matrix of TRIZ is based on knowledge and consists of 39 types of engineering parameters and 40 principles of invention to resolve conflicts, as presented in Table 5. The characteristics to be improved are placed along the vertical axis, and the horizontal axis is used for characteristics that deteriorate. The solutions of 40 principles can be found at the intersection between two parameters.

Table 4. Determination of Key Functions Using the F-HOQ

| Required functions | Quality characteristics | Absolute priority | Priority Ratio (%) | Ratings |
|-------------------|-------------------------|-------------------|--------------------|---------|
| Compatible with ISO container ships | | | | |
| Low shipping cost | | | | |
| Small number of components | | | | |
| Low manufacturing cost | | | | |
| Large space inside modules | | | | |
| Small deflection under loads | | | | |

Table 5. Example of Contradiction Matrix. (Altshuller et al. 2002)

| Characteristic | Characteristics that deteriorate |
|---------------|--------------------------------|
| Weight of a mobile object | 26, 30, 35, 3 |
| Volume of a stationary object | 1, 31, 35, 37 |
| Capacity | 35, 26, 12, 17 |
| Sales point | 24, 37, 28, 24 |

Table 5 shows the processes of identification of contradictions using the F-HOQ. Rooms A and B of the F-HOQ are used to identify technical contradictions. Room A of the F-HOQ shows the correlation among the QCs. Two characteristics with a negative correlation in room A are converted into two of the 39 parameters of TRIZ. Similarly, room B shows the correlation among functions. "IFR" of room B in Fig. 5 indicates the ideal final result for each function. If a
negative correlation exists between two functions, they are also converted into two of the 39 parameters of TRIZ.

Table 6. Contradictions of QCs

| Improved QCs | Parameters | QCs that deteriorate | Parameters |
|--------------|------------|----------------------|------------|
| QC01         | 8. Volume of a stationary object | QC03 36. Complexity of a device |
| QC02         | 2. Weight of a stationary object | QC05 13. Stability of composition, 14. Strength |
| QC04         | 33. Convenience of use | QC05 13. Stability of composition, 14. Strength |

Table 6. lists three pairs of converted parameters from among the QCs for which contradictions exist. Table 7. lists the converted parameters from room B of the F-HOQ. The parameters converted from the QCs and functions are rearranged in the contradiction matrix presented in Table 8.

Table 7. Contradictions of Functions

| Improved function | Parameter | Functions that deteriorate | Parameters |
|--------------------|-----------|----------------------------|------------|
| F02-2              | 8. Volume of a stationary object | F03-1 13. Stability of composition |
|                    |           | F03-2 13. Stability of composition, 14. Strength |

Table 8. Contradiction Matrix and Its Solutions. (Altshuller et al. 2002)

| Characteristics that deteriorate | 13 | 14 | 36 |
|---------------------------------|----|----|----|
| Improved characteristics        | 2  | 26, 39 | 28, 2 |
|                                 | 1, 40 | 10, 27 |
|                                 | 8  | 34, 28 | 9, 14 |
|                                 | 35, 40 | 17, 15 |
|                                 | 33 | 32, 35 | 32, 40 |
|                                 | 30 | 3, 28 |

Fig.5. Identification of Contradictions Using the F-HOQ
3.4 Solution Derivation Process

Possible solutions can be derived by following the process described below:

- Step 1: Find QCs that have negative correlations and convert these QCs into two of the 39 parameters of TRIZ.
- Step 2: Find functions that are strongly correlated with the QCs of step 1.
- Step 3: Refer to the contradiction matrix corresponding to the function and QCs in step 2 and find solutions.

Fig.6 shows an example of the solution derivation procedure. QC1 "volume of modules for delivery" and QC3 "number of components per unit volume" have negative correlations. These QCs are converted into "volume of a stationary object" and "complexity of a device," respectively. These two QCs are strongly related with the function F01-02 "form outside the module." By referring to the contradiction matrix, two invention principles "principle 1: Segmentation" and "principle 31: Porous material" are recommended.

The contradiction matrix of the quality characteristics that have a correlation with F01-02 "form outside the module" is shown in Table 9. The invention principles TRIZ provide the solutions that can resolve contradictions.

Table 10 presents the process of solution derivation for function F01-02. Two principles, namely, "Segmentation" and "Porous materials" are used for solving the contradiction. The same process can be applied to other functions.

Table 9. Contradictions Matrix for function F01-2

| Characteristics that are getting worse | 13 | 36 |
|---------------------------------------|----|----|
| Characteristics to be improved         | 8  | 34, 28, 35, 40 |
|                                       | 1, 31 |

Table 10. Solution Derivation for F01-02

| Level 2 function | Form outside the module |
|------------------|-------------------------|
| Level 3 functions|                         |
|                  | F01-2-A column, F01-2-B beam, F01-2-C Floor panel, F01-2-D Wall panel |

"Principle 1: Segmentation": All components need not be delivered as a unit module. The building can be segmented into modules and non-modules. Components other than the modules are manufactured as columns, beams, floor panels, and wall panels. Modular units are offset stacked, with non-module components installed between modules.

"Principle 31: Porous materials": Segmented components are loaded into other modules and delivered to the site. A modular unit is used as the porous material.

| Design factors | Design span between modules for site installation of panels shorter than 5 m. The size of panels is determined considering the possibility of loading inside the modules. |
|----------------|---------------------------------------------------------------------------------------------------------------|
4. Design Results and Verification of CTQs

Fig. 7. shows the design result of the developed modular unit. Corner casts that are compatible with ISO containers are used at the upper and lower corners of a unit. The upper corner cast is temporarily used during delivery; it is removed after the module is connected at the construction site.

Fig. 8. compares the total volumes of the existing system and design result. The development helped reduce the total volume of modules for delivery (622.9 m$^3$) by 48.0% as compared to the currently used system (1197.7 m$^3$). The new developed system is also compatible with ISO container ships. Fig. 9. shows the final design of the exportable modular building.

Fig. 9. Final Design Result of Exportable Modular Building

Table 1. Verification of CTQs

| CTQs                        | Existing system | Design result |
|-----------------------------|-----------------|---------------|
| Volume of transportation    | 1197.74 m$^3$   | 622.9 m$^3$   |
| Weight of frames per unit area | 0.59 kN/m$^2$ | 0.42 kN/m$^2$ |
| Ratio of ceiling height to module height | 0.85 | 0.85 |

5. Conclusions

In this paper, the authors propose a new product development process called the F-HOQ. This methodology integrates TRIZ and two phases of QFD. The F-HOQ provides a tool for designers to reflect customers' needs in the development of products systematically. By applying the proposed F-HOQ process to the development of an exportable modular building system, the volume of modules for delivery
and weight of frames per unit area were significantly reduced as compared to the existing system. The proposed F-HOQ can be used as a customer-driven innovative methodology for developing new products in the field of construction. The results of a case study show that by applying the new method, the volume of an exportable modular building system compatible with ISO container shipping was reduced by 48% and the weight of structural steel was reduced by 30%.

Acknowledgement
This research was supported by a grant from the National Research Foundation of Korea (Grant number: NRF-2016 R1D1A1B01010615).

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