QFD Model Based on a Suitability Assessment for the Reduction of Design Changes in Unsatisfactory Quality

Jaeyoul Chun¹ and Jaeho Cho*²

¹Professor, Department of Architectural Engineering, Dankook University, Korea
²Research Professor, Department of Architectural Engineering, Dankook University, Korea

Abstract

When a design project is executed, inappropriate decisions in the selection of materials, construction methods, and systems negatively impact the productivity of the project since such decisions result in inadequate design. Subsequently, these defects become a cause for design changes. In order to prevent such cases, clear RPC (Requirement Performance Criteria) should be provided in order to allow for suitable design alternatives, and a quality review should be undertaken by tracking alterations in the requirements, as these continuously change and update. This study suggests a quality function deployment (QFD) model that is based on a suitability assessment (QFD-SA) to prevent design changes that result in unsatisfactory quality. The suggested assessment model is able to define the function and performance requirements, and it is thus suitable for use when selecting design alternatives for those requirements. The model uses a matrix technique in its assessment, and furthermore, the QFD-SA assessment model reanalyzes the degree of conformity according to the changes in the RPC.

Keywords: QFD (Quality Function Deployment); design change; requirement; performance; suitability

1. Introduction

Design changes inevitably occur during the building design process. There can be a number of causes for these design changes, including amendments in regulations, additional client needs, changes in the original requirements, design errors caused by the designer, missing functions, and alternative selection errors. An investigation performed by the Procurement Agency, which is the representative institution that places design orders for domestic facilities, pointed out that inadequate design and subsequent design changes are a major factor that negatively impacts facilities (Procurement Agency 2004).

According to an investigation on the frequency of flaws during the design review of apartment houses and office buildings (Kwak and Kim 2010), alternative selection errors and missing functions were the most frequent source of design defect. A lack of a usability review performed by the client, missing representations on the drawings, and discrepancies in the information between the different construction works followed, in that order. Another study indicated that insufficient requirement definitions and insufficient sharing of information between project stakeholders were major causes of design changes (Isacc and Navon 2008).

Design errors, missing functions, and alternative selection errors are among the various causes of design changes that can possibly be improved by quality management activities performed by administrators. The above mentioned factors altogether represent the types of design changes that can occur and subsequently result in unsatisfactory quality, which means that there are inconsistencies in the work with respect to the requirements of the design. In contrast, the additional needs of the clients and changes in the original requirements result in somewhat different characteristics for the design work. These are situations that occur due to uncertainty of design work and to the nature of collaborative work involving numerous stakeholders.

In conclusion, all of these factors are caused by inadequate criteria for the requirements or by discrepancy between the requirements and the design solutions. Hence, the causes for design changes resulting from unsatisfactory quality may be classified into two categories: first, discrepancies between the required quality and that of the design solution; and second, vague descriptions of the RPC. Fig.1. below shows a schematic of the types of design changes resulting from unsatisfactory quality, among the entire causes for design changes. As a result, clear criteria
should be presented with respect to the required quality and the proper decision-making technique for an assessment of quality conformity should be performed in order to reduce the number of design changes due to unsatisfactory quality.

**Scope of Design Change**

1. Unavoidable Natural Disasters, 2. Change of Legal System
3. Civil Complaints, 4. Initial Plan Change, 5. Defective Construction Statement
6. Safety Assurance Problem, 7. VE (Value Engineering), 8. Innovation Methods

**9. Unsatisfactory Quality Type Design Change**

2. Methods and Ranges of Study

This study proposes a decision-making technique that is based on RPC for the assessment of quality conformity and suitability, and undertaken by performing the following steps.

(1) Evaluate the status of the existing research. The themes of the research were categorized into two categories, including 'study of the reduction of the design changes' and 'study of the decision-making technique'. (2) Determine the causes for the design changes of an unsatisfactory quality type via case investigation. (3) Propose a process for quality management following alterations in the requirements. (4) Propose a quality assessment model based on suitability according to the RPC. (5) Validate the utility of the QFD-SA model by analyzing specific cases. (6) Address the conclusions of this study.

**3. Literature Review**

The existing research was surveyed and the themes of the relevant studies were divided into two categories: the 'study of design changes' and the 'study of decision making techniques'.

(1) Study of Design Changes in Building

Studies discussing design changes have been actively conducted both within Korea and abroad. With respect to domestic research, the majority of these have focused on performing environmental analyses of design changes, related policy issues, cooperative design methods, and quality management processes that prevent design changes.

Ahmed et al. (2003) implemented a QFD model as an assessment tool to find alternatives to design changes and to keep track of the requirements requested by the owner. In addition, they suggested a new method to manage information on the requirements of the project as well as to communicate the process for the design changes. Oh (2007) analyzed the factors that could result in design changes in construction projects, and suggested ways to improve the construction changes in the environment. Isaac and Navon (2008) examined the causes for interruptions that occur in functions specified in design changes, and also proposed a tool for automated design changes that allow users to trace relationships that exist between the given requirements and the design production. This ensures that the stakeholders involved in the decision process, in which change proposals are evaluated, will know the scope of the implications of the change in advance. Kim et al. (2009) analyzed the main cause for design changes that have occurred during building construction and proposed a process model that supports those design changes. Lee and Chun (2012) also investigated design changes and proposed a quantitative assessment method that could handle alternative designs by taking into account cost, performance, and constructability. Despite systematic approaches to the causes and problems of design changes that we have seen when discussing existing research, it was revealed that the proposal of a quality assessment model were very rare in order to improve inadequate design and the proposals of processes in order to improve unsatisfactory quality.

(2) Study of Decision Making Techniques

Decision-making during the design process should be undertaken with caution since the subsequent phase directly affects the next phase. In particular, inappropriate decision-making during the planning phase and the schematic design phase results in various forms of productivity loss since those decisions themselves become a direct cause of design changes at the construction document phase or construction phase.
The Analytic Hierarchy Process (AHP), Forced-Decision Method (FDM)/Improved Weight Decision Method (IWDM), Weighted Comparison Matrix method (WCM), VE-Matrix Evaluation Method, and QFD are decision-making techniques that are broadly utilized in both industry and academia.

Lee and Chun (2009) utilized the FDD/IWDM method to evaluate the alternatives. The features of the FDD/IWDM method are that the relative priorities of the function can be evaluated.

The VE-Matrix Method uses a rating scale for linguistic assessment (Caltrans Value Analysis Report Guide, 1999). In this scale, the function ideas are evaluated by using a 10-point rating scale. The VE Matrix Method allows users to evaluate performance and to set the priorities of the functions. Users can then set the evaluation items, such as the degree of satisfaction of the function, constructability, and economic feasibility. The VE Matrix Evaluation method is then used to choose the optimal alternatives by estimating the priorities of each of the evaluation items, and as a result, this method is suitable for a comparison of the quality of the design alternatives.

In addition to the three methods mentioned above, QFD is has also been considered as a representative method for decision-making. The QFD method is a quality assessment method that can be widely used in industry, and it was created by Mitsubishi in 1972.

This method analyzes the function and the performance that comprise quality by converting the client's requirements into a design quality definition. The components of the QFD are the client's requirements, extraction of quality factors in the requirements, estimation of the priorities in the required quality, and a weighting priority conversion. Kwak (2011), Yoo and Yi (2005), and Yang and Kim (2005) used QFD to perform a quality assessment. Prasad (2013) evaluated product quality in terms of economic feasibility. The VE-Matrix Evaluation method is then used to choose the optimal alternatives. The features of the QFD method are decision-making techniques that are broadly utilized in both industry and academia.

QFD has strengths and weaknesses as follows. The QFD method creates a novel idea, mainly by considering the performance priorities for quality and by focusing on quality improvements. While the RPC may be defined by the QFD, the degree of suitability of quality based on the RPC may not be evaluated. As we have discussed, research related to the decision-making techniques discussed above have revealed that decision-making techniques are able to assess the value scores by focusing on function.

Although several methods for a quantitative evaluation of the function and the performance have been suggested, a research theme has not yet found a conformity assessment and suitability assessment according to the RPC.

4. Analysis of the Causes of Design Changes due to Unsatisfactory Quality

Design changes are caused when a design is not suitable for any of the project requirements in terms of the schedule, cost, or quality. In addition, design change factors exist over the entire scope of the construction project, such as alterations in the client's requirements, amendments to the regulation systems, and a diversification of the construction methods.

It is impossible to conduct perfect schematic design and design development that does not involve design changes. Table 1. below shows the results of investigation on cases of design changes based on 26 cases of private office buildings.

The factors that cause design changes can be categorized by items and by operating organization. The operating organizations that cause design changes have been revealed as designers in the first place, clients in the second place, and contractors in the third place. The items that cause design changes are shown as 'changes in schematic design' first, 'material changes and quantity growth' and 'ambiguous design and missing function' second, and 'inconsistency in design solution based on field conditions' and 'client's additional requirements' third.

This study does not present the representative causes for all design changes, but only provides a rough list of the causes. The results shown in Table 1. allow us to deduce the design changes that were caused with respect to quality.

The change types, including schematic designs, fluctuations in quantity, civil complaints, and unpredictable natural disasters are natural phenomena that are caused by uncertainty, which is part of the nature of architectural design. Improvements in the design quality, including changes from such causes, require different approaches. However, the types including 'ambiguous design', 'missing function', and 'selection error of the construction methods' are considered as the type of design changes that are a result of unsatisfactory design. These, in turn, are caused when the quality of the design does not meet the necessary quality threshold, or when the requirements are not clearly defined. The 'inconsistency with field conditions' item is another cause for design changes that are due to unsatisfactory quality, and it is highly related to the 'interference among building system functions', 'function errors' and 'performance discrepancies'.

The following issues should be reviewed in order to reduce the occurrence of such items.

① Check if the design alternatives show conformity to the required performance criteria of the field project.

JAABE vol.14 no.1 January 2015

Jaeyoul Chun

115
2. Check if the performance of the design alternatives interferes with that of adjacent systems.

3. Check if there are self-contradictions between the functions of alternative design.

Fig. 2. shows the concept diagram of the quality suitability and the causes for design changes of an unsatisfactory quality type.

5. Quality Management Process Based Upon Changes in Requirements

Clear definitions of the required functions are essential for the selection of design alternatives since each project has unique characteristic and properties. In addition, changes in the required function and in the RPC frequently occur as a result of the innate nature of the design process.

The RPC is redefined during a mutual review process by experts from each design discipline, and these are continually revised during the design process. Therefore, the assessment of conformity and the suitability of the design alternatives should be performed in an environment with continuously changing requirements. A concept diagram of the design quality management for the changes in the requirements of each phase of the design process is shown below in Fig. 3.

Since changes in the requirements also alter the RPC, technical decision-making is required to solve conflicts with existing systems and interference between the requirements.

6. QFD Model based on Suitability Assessment

The ‘QFD-SA’ method adopts the CVAG (Caltrans Value Analysis Guide, 1999) linguistic assessment. A 5-point Likert scale is used to assess the function priority.

The QFD-SA method and the QFD method share a common feature for defining the relevance of the performance items related to function. The QFD-SA method differs from the QFD method in respect of suitability against the RPC.

The RPC may be defined as the minimum performance values or as the recommended performance values. These criteria are related to functions that are utilized in the assessment of the conformity and the suitability through a comparison with the given RPC. A concept diagram of the suitability assessment is presented in Fig. 4.

The suitability scale is ‘0’ when the required performance criteria are the same as the performance of the alternatives; and a zero value is used for strict conformity. For example: if the performance value of

Table 1. Analysis of the Factors Concerning Design Changes (The 26 Cases of Office Buildings)

| Item | Causes of the Design Changes | Owner | Designer | Contractor | Frequency | Ranking | Relation |
|------|------------------------------|-------|---------|------------|-----------|---------|----------|
| 1    | Additional Client's Needs    | 10    | -       | -          | 10        | 3       | Quality  |
| 2    | Selection Error of Construction Methods | - | - | 9 | 9 | 4 | Quality |
| 3    | Material Changes, Quantity Growth | 5 | - | 7 | 12 | 2 | Quality |
| 4    | Inconsistencies in the Design and the Field | - | 10 | - | 10 | 3 | Quality |
| 5    | Inadequate Schematic Design | - | 8 | - | 8 | 5 | Quality |
| 6    | Change in the Schematic Design (Volume of Space) | 12 | 14 | - | 26 | 1 | Quality |
| 7    | Unclear Design, Missing Features, Design Errors | - | 12 | - | 12 | 2 | Quality |
| 8    | Omission of Construction Statement (bill) Item | - | - | 8 | 8 | 5 | Cost |
| 9    | Civil Complaints | 4 | - | 2 | 6 | 7 | - |
| 10   | Safety Assurance | - | 7 | - | 7 | 6 | Quality |
| 11   | Unpreventable Natural Disasters | 2 | 1 | 2 | 5 | 8 | - |
the alternative is higher than the RPC by a score of 2 in the performance ratings, then the suitability score is 2. If the performance value of the alternative is higher than the RPC by a score of 1, then the suitability score is 1, if the performance value of the alternative is equivalent to the minimum performance, then the suitability score is 0, if the performance value of the alternative is lower than the RPC by a score of 1, then the suitability score is -1, and if the performance value of the alternative is lower than the RPC by a score of 2, then the suitability score is -2, etc.

In the case of the other scales, such as the nominal scale or the binary scale, the suitability scale is also readjusted according to the normalization of the zero rating point. Fig. 5, presents the basic format of the 'QFD-SA' method.

**Fig. 4. Conceptual Diagram of Conformity and and Suitability**

**Fig. 5. QFD Concept Model-based on a Suitability Assessment**

1. **Function Definition (FD):** The process for defining a function is proposed in the literature and is related to VE and the 'FAST Diagram' method. The defining function in this study shows only the detailed definition of the function.

2. **Function Weight (FW):** The function weight is determined by using a 10-point scale. For example: maximum priority = 10 points, moderate priority = 5 points, minimum priority = 1 point.

3. **Performance of Design Solution (PDS):** The performance is evaluated and classified into 5 ratings. For example: the 5th rating is a score of 5, the 4th rating a score of 4, the 3rd rating a score of 3, the 2nd rating a score of 2, and the 1st rating a score of 1. In the case where the performance evaluation for the alternatives is either a nominal rating or a binary rating, such a scale readjusts to the corresponding rating to provide a normalization score.

4. **Correlation Analysis of Function and Performance (CAFP):** The correlation between the function and the performance is evaluated. For example, an extremely high correlation (●) has 1 point, a high correlation (○) has 0.8 points, a moderate correlation (▲) 0.6 points, and a low correlation (▽) 0.4 points. The scale of the correlation is not absolute, and the user can choose among various scales.

5. **Satisfaction Analysis for Required Performance Criteria (SARPC):** Review the quality satisfaction through a comparison of the RPC that are specified in the design guidelines and the performance grade of the product alternative. Dissatisfaction mark (▲) is presented. And satisfaction mark (●) is presented.

6. **Interference Analysis for Required performance Criteria (IARPC):** One value of the RPC is set as the standard, and an interference mark (△) is presented, when the RPC differ from one another. If no interference occurs, it is presented with (-).

7. **Function Satisfaction Analysis (FSA):** Review the function satisfaction through a comparison with the required performance criteria. FSA is determined, when the suitability score is the same as, or higher than 0 point. The function satisfaction is presented with (△). Function dissatisfaction is presented with (○).

8. **TFSS (Total Function Suitability Score):** Assign the suitability scores by comparing the performance values of the product. TFSS (Total Function Suitability Score: V) for the design alternatives are estimated by summing up the FSS.

\[
V = \sum_{i=1}^{n} \sum_{j=1}^{m} v_{ij} \cdot w_{ij} \cdot x_{ij}, \quad i = 1, 2, ..., m \quad j = 1, 2, ..., n
\]

\[
(v) \text{ is Function Suitability Score (FSS).} \quad (w) \text{ is Function Weight (FW).} \quad (r) \text{ is Correlation Score (CS).}
\]

9. **SIUL (Suitability Index based on Unsatisfactory Level):** This value is the sum of the FSS that are less than 0 divided by the absolute maximum total of SUSS.

\[
S_{k} = \frac{d_{k}}{\max(d_{k})}, \quad (d_{k} < 0, -1 \leq S_{k} < 0) \quad (1)
\]

\[
S_{k} = \text{SIUL for Design Solution}(k).
\]

\[
d_{k} = \sum_{i=1}^{m} \sum_{j=1}^{n} v_{ij} \cdot w_{ij} \cdot x_{ij} \quad \text{----------------------------------------} (2)
\]

\[
d_{k} = \text{Sum of Unsatisfactory Suitability Score (SUSS)}.
\]
**SISL (Suitability Index based on Satisfactory level):** This value is the sum of the suitability scores that are greater than 0 divided by the maximum total of SSSS.

\[
s_{i}^{*} = \frac{\sum_{i=1}^{n} v_{i}^{*}}{\max(d_{i}^{*})}, \quad (d_{i}^{*} \geq 0, 0 \leq S_{i}^{*} \leq 1) \quad \text{(4)}
\]

\[S_{i}^{*} \text{ is SISL for Design Solution } k \text{.}
\]

**TFCI (Total Function Conformity Index):** This value is the estimated CSS divided by the maximum SSSS or the maximum SUSS. For the negative sums of CSS, the estimated CSS are divided by the maximum SUSS. For the positive sum of CSS, the estimated CSS are divided by the maximum SSSS.

\[
v_{i}^{*} = \frac{S_{i}^{*}}{\max(v_{i}^{*})}, \quad (0 \leq S_{i}^{*} \leq 1) \quad \text{(6)}
\]

\[s_{i}^{*} \text{ is Satisfactory Suitability Index of Function } (SSIF). \]

**FCD (Function Conformity Deviation):** The FCD is obtained by calculating the distance between the SIUL and the SISL. The Sub-Function Conformity Deviation (SFCD) is the distance between the USIF and SSIF.

7. Case Study

In order to verify the validity of the ‘QFD-SA’ method, the suitability was evaluated for the required function that was initially planned, and then it was compared against the suitability of the required function that was altered.

1) Summary of the Case Study

The QFD-SA technique can be applied to window design. Windows are expected to have several characteristics, such as insulation performance (Heat Transmittance: U Value), Solar Heat Gain Coefficient (SHGC), Visible Light Transmittance (VT), Air Leakage (AL), Condensation Resistance (CR), and Outdoor Indoor Transmission Class (OICT). Thermal comfort in spaces (a required function) can be determined by the complex performance of these features. Window performance and the standard rating grades that have been analyzed are summarized below in Tables 2. and 3.

Table 2. Performance Value of the Alternative Design Solutions

| Solutions | U-Value | SHGC | VT | AL | CR | OITC |
|-----------|---------|------|----|----|----|------|
| Alt-(1)   | 0.49    | 0.33 | 0.55 | 0.20 | 71 | 32  |
| Alt-(2)   | 0.38    | 0.48 | 0.35 | 0.25 | 30 | 27  |
| Alt-(3)   | 0.47    | 0.52 | 0.50 | 0.24 | 58 | 27  |
| Alt-(4)   | 0.31    | 0.46 | 0.55 | 0.36 | 49 | 35  |

Table 3. Performance Utilizing a 5-Point Rating Scale

| Performance | Grade-5 (score 5) | Grade-4 (score 4) | Grade-3 (score 3) | Grade-2 (score 2) | Grade-1 (score 1) |
|-------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| U-factor    | 0.00 – 0.20       | 0.20 – 0.40       | 0.40 – 0.60       | 0.60 – 0.80       | 0.80 – 1.00       |
| SHGC        | 0.20 – 0.30       | 0.30 – 0.40       | 0.40 – 0.50       | 0.50 – 0.60       | 0.60 – 0.70       |
| VT          | 1.00 – 0.80       | 0.80 – 0.60       | 0.60 – 0.40       | 0.40 – 0.20       | 0.20 – 0.00       |
| AL          | 0.00 – 0.10       | 0.10 – 0.20       | 0.20 – 0.30       | 0.30 – 0.40       | 0.40 – 0.5        |
| CR          | 100 – 80          | 80 – 60           | 60 – 40           | 40 – 20           | 20 – 0            |
| OICT        | 40 – 36           | 30 – 32           | 32 – 28           | 28 – 24           | 24 – 20           |

Fig. 6. The Case Analysis of the QFD-SA for Alternative (1)
The RPC is defined to comply with the design guidelines for the characteristics of insulating windows in the North-central United States, which has a similar climate to Korea (i.e. mixed hot and cold climates).

(2) QFD-SA Case Study based on the Definition of the Original Function

Fig. 6 shows a case of the function assessment for Alternative (1) based on the QFD-SA method. The SIUL was evaluated as -0.09 in the analysis of Alternative (1).

The SISL was revealed to be +0.09, and the TFSS was obtained as 0.49. The TFCI for Alternative (1) was calculated as 0.01, and the FCD for Alternative (1) was calculated as 0.18 (0.09 + (-0.09)).

(3) A Case of the QFD-SA Analysis based on the Definition of the Changed Function

The requirements are changed based on the RPC. Alterations in requirements occur due to the client's additional request concerning improvement in thermal insulation performance and reduction in cooling load during summer time. The following 4 changes were made in the function.

Change in the FW: function 1 (from 4.3 to 6.2), function 5 (from 4.8 to 7.8), and function 8 (from 4.3 to 8.0).

U-Value performance ratings for function 1 and function 5: Changed from the 3rd rating to the 4th rating.

SHGC performance rating for function 1: Changed from the 4th rating to the 5th rating. (Grade 5 of SHGC performance reduces energy cost by blocking more solar heat compared to Grade 4.)

AL rating for function 1, function 5, and function 8: Changed from the 3rd rating to the 4th rating.

The QFD-SA analysis is performed again according to the changes in the RPC. The analysis for Alternative (1) is based on the alterations in the requirements that were revealed in the SIUL function as -0.13. The SISL was obtained as +0.04. The TFSS was -11.29. The TFCI for Alternative (1) was evaluated as -0.16, and the FCD of the alternative was calculated as 0.17.

(4) Discussion of the Analysis

Once the RPC are determined, the FCI is obtained according to the performance value of the design alternatives. A closer FCI, TFCI consists of 0 points, which is the greatest conformity that can be achieved with respect to the required function. Also, the higher the FCI and TFCI, the greater the satisfaction with respect to the required function that is thought to be obtained. Although the design alternative shows a high value for TFCI, the alternative is considered to be unsuitable in the design if an SIUL arises to some extent.

Therefore, both the FCI and the SIUL should be considered for proper selection of an alternative. Fig. 7 presents the results of a QFD-SA analysis based on the definition of the original requirements for 4 design alternatives, and the changes in the requirements for the 4 design alternatives, respectively.

For QFD-SA based on the original definition, 'Alternative 1' recommends the proper design that shows the minimum SIUL of -0.09 with the TFCI of 0.008 (about 0.01). On the other hand, 'Alternative 4' shows the SIUL of -0.16 with the TFCI of 0.014 (about 0.01).

For the QFD-SA based on the change definition, 'Alternative 1' is recommended as the proper design alternative, which shows the SIUL of -0.13 with the TFCI of -0.16. 'Alternative 1' has the minimum SIUL of -0.13 and the highest TFCI of -0.16.

In conclusion, the decision makers are not able to...
clearly recognize an SIUL if the QFD-SA analysis is not performed by defining the RPC. The absence of an objective evaluation standard may result in a defect in the decision making with the selection of design alternatives. Unsatisfactory function with respect to the RPC is a major cause of design changes.

8. Conclusion
These Design changes of an unsatisfactory quality are caused by ambiguous requirements and by insufficient quality assessments. A clear definition of the required function should be obtained, first of all, in order to secure the quality required, and thus prevent additional design changes. A clear recognition of the requirements and the implementation of the assessment based on the RPC allow for a significant reduction in the design changes that occur due to unsatisfactory quality.

The QFD-SA quality assessment model that is proposed in this study supports assessments for the conformity and suitability of design alternatives, according to the RPC. The QFD-SA method provides a quantitative evaluation of the quality satisfaction for function and performance that design alternatives have. The following are the improvements of the QFD-SA method in terms of the definition, analysis, and the evaluation of quality.

(1) It allows for a reflection of both the definition of the required function and alterations that the client intends. (2) It allows for an evaluation of the priority of the function, and that of the related performances. (3) It allows for an investigation of the self-interference between the performances of the required function in advance. (4) It allows for an analysis of the conformity and suitability of the design alternatives based on the RPC. (5) It allows for the management of the suitability range of the quality by calculating a SIUL and SISL. (6) It allows for an analysis of the conformity and suitability of design alternatives, based on the RPC.

A future study aims to investigate the broader utilization of QFD-SA by adopting it on a compound scale that consists of a nominal scale, a binary scale, etc. In addition, an assessment system for design quality that can be utilized in a web environment will also be developed.

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