DEVELOPMENT OF DESIGN FOR AUTOMATION (DFA) BASED ON QUALITY FUNCTION DEPLOYMENT

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ABSTRACT: Recently, the building construction industry has been forced to cope with lack of skilled labor. A robot-based construction automation system should help overcome crucial troubles which may be caused by this phenomenon. In particular, it is vital to propose design for automation (DFA). Quality function deployment (QFD) is applied a systematic aid in determining the design reflecting customer's needs. This study employs the QFD approach to plan the component designs of an effective automation process, and presents the development process of DFA with an illustrative project. As a result, the study identifies the developers' design requirements for automated construction and weights them by their importance indices.

Keywords: Design for Automation (DFA); Quality function deployment (QFD); design requirements

1. INTRODUCTION

In the construction industry, projects are more labor-intensive than those in the manufacturing industry. For this reason, the quality of a building and its construction cost and time are largely influenced by the skill of the workforce. In addition, the recent aging of the workforce and the lack of skilled labor may cause major troubles in the construction industry.

Robotic-based construction automation systems are currently being employed as an effective alternative for labor [1]. The bigger and more multifunctional building projects have gradually been deploying such systems. To achieve efficient construction automation processes, design for automation (DFA), including the modification of component design and construction processes to facilitate the operation of automated equipment should be implemented at an early design stage with the development of a core technology, which is described as the control of sensor-based robots [2].

Quality function deployment (QFD), which has been used for the development of new products in manufacturing industry, is a useful and systematic planning tool for translating customer's requirements into design characteristics. The major benefits of QFD are the reduction of design changes and the improvement of product quality satisfying customers [3]. Recently, QFD has also been applied to deriving well-defined designs of construction projects by identifying the significant characteristics and enhancing the mutual communication between clients and designers.

In Korea, the development of a automated construction system is actively progressing. We present a process for establishing DFA suitable for Korean construction automation, based on the QFD approach. Interviews and questionnaires were used to survey the researchers in the Robot-based Construction Automation (RCA) group to derive the important factors in the application of the automated construction system, which are concerned with customers' requirements and technical characteristics. Next, the factors were weighted by the computational process of the QFD. This study focuses on component designs for the automated construction system in Korea, which aims at the assembly of steel structures in high-rise buildings.

2. OVERVIEW OF THE AUTOMATED CONSTRUCTION SYSTEM

A research group in Korea aims at developing an economical and practical construction automation system appropriate to the circumstances of the Korean construction industry [4]. In this study, the development of the system involves three approaches based on the constraints of Korean construction sites. In the steel erection process, the core preceding method and H-shaped steel frames are adopted. The employment of existing technologies and partial automation has also been applied as one alternative for overcoming the difficulties of the technological environment and enhancing the new method's applicability.

With these approaches, the automated construction system for high-rise buildings has four core technologies:

planning and integration of the system; a construction factory (CF) with climbing hydraulic robots; a robotic crane for lifting steel frames; and an intelligent delivery system based on multidimensional CAD and RFID. Figure 1 shows a schematic diagram of the construction automation system introduced in this study.

Figure 1. Four core technologies in the RCA

Our robot-based construction automation (RCA) system is intended for automatic fabrication of major steel girders and beams. The intelligent tower crane hoists materials; it improves the existing tower cranes and is integrated with bolting robots and guardrails to deliver the lifted steel girders to the targeted points of columns. The construction factory (CF) with climbing hydraulic robots minimizes the impact of environmental elements such as weather and allows the robotic crane to operate accurately.

In this study, the design components of the automated construction system are classified into five parts: robotic crane, CF, climbing hydraulic robot, steel frames and joints, and core wall. The intelligent tower crane is excluded from the design components because it has no design elements.

3. APPLICATION OF QUALITY FUNCTION DEVELOPMENT (QFD)

3.1 QFD

In general, building construction produces a facility based on plans and specifications. It is important to identify clients' needs accurately and transform them appropriately into plans and specifications [5]. Quality Function Deployment (QFD) is a design management tool for identifying customers' requirements and reflecting them into design components [6]. QFD emphasizes the customers' preferences for design characteristics, provides a systematic means of ensuring that technical qualities appropriately reflect their needs with a set of matrices that provide information regarding the relationships between the characteristics. Thus, QFD is employed here to develop more efficient and practical design concepts in the early stages of applying the robot-based construction automation system to steel-framed high-rise buildings. In this study, customers are defined as the researchers and workers who participate in developing the automated construction system. On the basis of their design requirements, considerable elements are identified and weighted throughout the process shown in Figure 2.

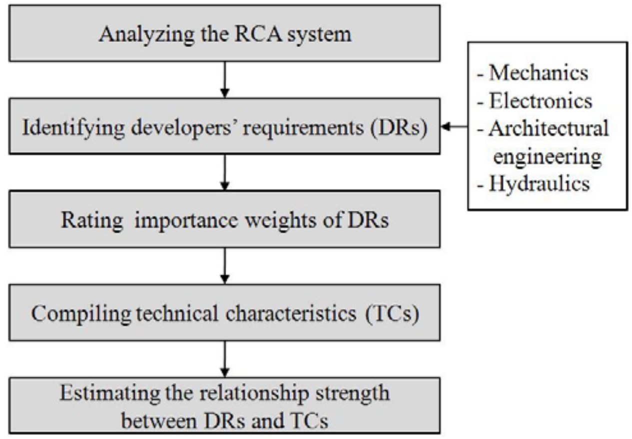

Figure 2. Assessment process of component designs by the QFD approach

3.2 Identification of Developers' Requirements (DRs)

In the application of the QFD approach to construction projects, customers may generally be clients, developers, suppliers, service providers, local authorities and other potential consumers [5]. However, in this study, they are confined to the researchers participating in developing the RCA system, because the system is in progress and there are no existing cases.

The research group organized a task-force team to derive the requirements for the main design components consisting of the system; robotic crane, the CF, climbing hydraulic robot, steel frames and joints, and core wall.

The interactive relationships between the components are shown in Figure 3. The team consists of a few experts in mechanics, electronics, architectural engineering, and hydraulics, as shown in Figure 4. Each member is assumed to have a full understanding of the RCA system. The task-force team conducted many discussions to reach consensus regarding the requirements, which are presented in Table 1.

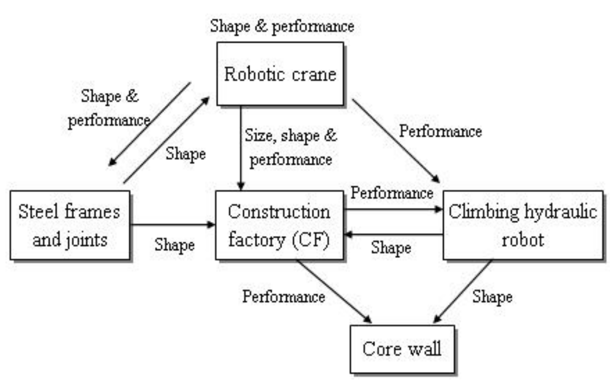

Figure 3. Interactive relationships between design components

Table 1. Developers' requirements and importance index

Components	Requirements	Importance index
Robotic crane	Bolting speed faster than labor's	70.9
	Exact recognition of positions of holes and bolts	87.3
	Robust bolting operation	90.9
	Movability to a target position	89.1
	Stability of position during bolting operation	81.8
	Automatic feeding of bolts and nuts	78.2
	Bolting operation regardless of the beam's size	58.2
	No interference when lifting materials	80
	Power supply	80
	Capacity to support bolting device during movement	78.2
Steel frame and joint	Providing adequate space for bolting operation	58.2
	Movement control of steel girder/beam before bolting operation	86.7
	Rotation control of steel girder/beam during transportation	81.7
	Easy operation of bolting device	62.2
	Ensuring accurate positioning for bolting operation	78.2
	Easy inspection after installation	56.2
Construction factory (CF)	Minimization of external environment's influence	81.7
	Providing adequate space for bolting operation	88.3
	Assembly and demolition of CF	71.7
	No interference when lifting materials	88.3
	Stable attachment during construction	86.7
	Minimization of displacement during robot movement and CF climbing	76.7
	Capacity to support robotic crane during bolting operation and movement	85
Climbing hydraulic robot	Precise flow control for minimizing deformation of CF	77.8
	Power supply	68.9
	Adequate oil pressure for climbing CF and robotic crane	86.7
Core wall	Installation of hydraulic system onto the external core wall	77.8
	Stable attachment of CF	93.3

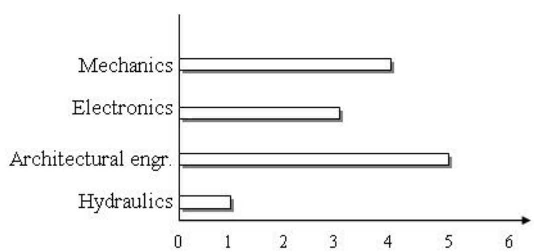

Figure 4. Organization of the task-force team

3.3 Rating the Importance Levels of the DRs

After identifying the developers' requirements for each component, a questionnaire was completed by the members of the task-force team to assess the degree of importance of each requirement. Generally, this survey also assesses the satisfactory levels of the existing conditions. However, the components of the automated construction system are new challenges that have rarely been applied to existing construction projects. For this reason, the levels are difficult to measure accurately and quantitatively, and consequently they are represented only by degrees of importance, which are scaled from five to one. One indicates "not important at all", while five means "very important". The importance levels for the requirements presented in Table 1 were calculated using equation (1).

$$\text{Importance Index} = \left(\sum_{i=1}^{5} w_i \times f_i\right) \times \frac{100}{5 \times n}, \qquad (1)$$

where n indicates the number of total responders, and w_i and f_i are the importance level and its frequency, respectively.

As can be seen in Table 1, the most important requirement in the robotic crane was robust bolting operation of which importance index represents 90.9. All requirements related to the robustness and accuracy of bolting operations were considered more important than the speed of the bolting operation. Capacity to support bolting device during operation and movement was also highlighted as important characteristics. Design of power supply was considered quite important than that in hydraulic system. Moreover, developers required consideration of automatic feeding of bolts and nuts.

Regarding the steel frame and joints, the main considerations were for movement and position control of steel girders and beams. These demands will require changes in joint's shape and guiding method of steel girders and beams.

With reference to the CF, providing adequate space for bolting operation showed the highest importance level as 88.3, while its importance index in steel frame and joint was 58.2. No interference when lifting materials in the CF as well as robotic crane was also considered fairly important because materials are transported through its roof. These will be reflected on the shape in the CF, bolting device, and rail. Besides requirements mentioned above, the main concerns were the stable attachment to the hydraulic system because the CF is a massive structure. This requirement was also mentioned as very important demand of core wall because hydraulic system is attached onto the core wall. In addition, assembly and demolition of CF was pointed out as a design consideration.

Adequate oil pressure for climbing was mentioned as the most important factor for designing the hydraulic system because the hydraulic robot lifts the CF and the robotic crane. Accurate fluid-pressure control between hydraulic robots was required to minimize deformation of the CF during its own climbing.

3.4 Technical Characteristics (TCs) and Correlations between the DRs and TCs

After identifying the demands and technical factors of each design component, their interactive relationships were found from consideration of researchers' requirements. The members of the research group suggested technical features based on their knowledge, experience, and relevant documents. The relationships are presented as correlated values and were derived during a few meetings of the task-force team. This process assists in determining the technical factors of each design component and prioritizing their impacts on component designs based on the needs. In this study, the scales proposed by Cohen [7] were used to assess the strength of the relationship with values of 1, 3, and 9, which indicate "strong correlation", "moderate correlation", and "possible correlation", respectively.

As shown in Tables 2 to 6, the strengths of the relationships between demands and technical factors are graded. The left column of the table shows the demands and their importance as computed using equation (1). The top section describes the technical factors to satisfy the demands.

As provided in Table 2, a bolting device that is regarded as core equipment requires designs of shape, size, weight, and movement speed. Especially, the shape has correlation all DRs except power supply, and influences strongly on the demands marked as ③, ⑤, and ⑧. Additionally, the development of sensing, remote-control, anchoring, and feeding device are required to satisfy the demands of the robotic crane. In particular, anchoring device has high correlation with the requirements for accuracy and speed of bolting operation.

The DRs in steel frame and joint are reflected on five technical characteristics as shown in Table 3. Length of column's bracket should be adjusted to provide adequate space for bolting operation according to the size of the bolting device. Joint's shape directly influences on the requirements marked as ②, ④, and ⑥.

Correlation between DRs and TCs in CF is listed in Table 4. The shape and size of CF and design of CF frame is required to satisfy the DRs. In addition, equipment for windproofing and protection against rain and snow are necessary to minimize the influence from external environment.

Table 2. Relationship matrix of robotic crane

Requirements \ Technical characteristics		Shape of bolting device	Size of bolting device	Weight of bolting device	Movement speed	Sensing device	Remote-control device	Anchoring device	Feeding device	Rail shape	Rail stiffness	Shape of rail support	Distance between rail supports	Power supply method	Size of power source
① Bolting speed faster than labor's	70.9	3	1	1	9	9		9	9					3	
② Exact recognition of position of the holes and bolts	87.3	3				9	9	9		3	3	3			
③ Robust bolting operation	90.9	9						3			3	1	1	3	
④ Movability to a target position	89.1	3	9	9	9		3			9	9	1	9	9	
⑤ Stability of position during bolting operation	81.8	9	1	3				9		3	9	3	9	1	
⑥ Automatic feeding of bolts and nuts	78.2	3							9						
⑦ Bolting operation regardless of the beam's size	58.2	3				9		9	9		3	3		3	3
⑧ No interference when lifting materials	80	9	9		1					9			3	3	3
⑨ Power supply	80		1	3	9			3						9	9
⑩ Capacity to support bolting device during	78.2	3	3	9	9					9	9	9	9		

Table 3. Relationship matrix of steel frame and joint

Requirements \ Technical characteristics		Length of column's bracket	Joint's shape	Jointing method	Transportation method	Method for guiding steel beam
① Providing adequate space for bolting operation	58.2	9	3	3	9	3
② Movement control of steel girder/beam before bolting operation	86.7		9	3		3
③ Rotation control of steel girder/beam during transportation	81.7				3	3
④ Easy operation of bolting device	62.2	3	9	9	9	3
⑤ Ensuring accurate positioning for bolting operation	78.2		1	3	3	1
⑥ Easy inspection after the installation	56.2	3	9			

Table 4. Relationship matrix of CF

Requirements \ Technical characteristics		Equipment for windproofing	Equipment for protection against rain and snow	CF shape	CF size	Distance between CF frames	Frame material	Jointing method between CF frames
① Minimization of external environment's influence	81.7	9	9	9	1			
② Providing adequate space for bolting operation	88.3					9		
③ Assembly and demolition of CF	71.7	3	3	9	9	3	3	3
④ No interference when lifting materials	88.3		9	9	3	9		
⑤ Stable attachment during construction	86.7	3	3	3	9	3	9	9
⑥ Minimization of displacement during robot movement and CF climbing	76.7	1	1	3	3	3	3	9
⑦ Capacity to support robotic crane during bolting operation and movement	85			3	3	9	3	9

Climbing hydraulic robot necessitates eight technical factors related to designs of hydraulic robot, power source, and joints with the CF as listed in Table 5. Of these, the number of hydraulic robots has high relationship with all DRs of hydraulic system.

Design of core wall needs to attach stably hydraulic system with the CF. Location of core hall and concrete strength of core wall should be considered to accomplish these requirements as can be seen in Table 6.

Table 5. Relationship matrix of climbing hydraulic robot

Requirements \ Technical characteristics		Shape of hydraulic robot	Distance between hydraulic robots	Number of hydraulic robots	Oil pressure of hydraulic robots	Jointing method with CF	Number of joints	Flow control method	Size of power source
① Precise flow control for minimizing deformation of CF	77.8	9	3	9	9	9	9	3	
② Power supply	68.9	9	3	9		1		1	9
③ Adequate oil pressure for climbing CF and robotic	86.7	3	1	9	9			3	

Table 6. Relationship matrix of core wall

Requirements \ Technical characteristics		Location of core hall	Concrete strength of external wall
① Installation of hydraulic system onto the external core wall	77.8	9	1
② Stable attachment of CF	93.3		9

Table 7 presents the absolute weight (*AW*) and relative weight (*RW*) of each technical factor, which are computed by the equation (2) below.

$$AW = \sum (Importance\ Index \times Correlation\ Score)$$

$$RW = \frac{AW\ of\ each\ factor}{\sum AW\ with\ each\ component} \times 100 \qquad (2)$$

From the *AW*s and *RW*s, the prioritized technical characteristics are mostly concerned with the shapes of components. The weights of robot shape reflect about 11.4% in the design of the robotic crane. The joint's shape in the section of steel frames and joints represents about 31.3%. As a result, the RCA system may require joint's shape fairly different from the existing. The CF shape contributes about 18.8% of the total relative weight, and the *RW*s of shape of hydraulic robots are about 18.9%. These technical factors have great influence on demands with high importance indices.

Moreover, anchoring device represents about 9.9% as second highest rank of the RWs in robotic crane. In regard to the CF, the most important technical characteristic is the distance between CF frames, which has influences on all requirements except the item marked as ① in Table 4.

Table 7. AW, RW and ranking of TCs

Components	TCs	AW	RW (%)	Ranking
Robotic crane	Shape of bolting device	3660.0	11.4	1
	Size of bolting device	1989.2	6.2	9
	Weight of bolting device	2062.0	6.4	8
	Movement speed	2943.8	9.1	4
	Sensing device	1947.6	6.1	10
	Remote-control device	1053.0	3.3	14
	Anchoring device	3196.5	9.9	2
	Feeding device	1865.7	5.8	11
	Rail shape	2733.0	8.5	5
	Rail stiffness	2951.1	9.2	3
	Shape of rail support	1565.7	4.9	12
	Distance between rail supports	2572.8	8.0	6
	Power supply method	2503.7	7.8	7
	Size of power source	1134.6	3.5	13
Steel frame and joint	Length of column's bracket	879.0	13.1	5
	Joint's shape	2098.7	31.3	1
	Jointing method	1229.1	18.3	3
	Transportation method	1563.3	23.3	2
	Method for guiding steel beam	944.6	14.1	4
Construction Factory (CF)	Equipment for windproofing	1287.2	8.3	7
	Equipment for protection against rain and snow	2081.9	13.4	5
	CF shape	2920.5	18.8	2
	CF size	2257.3	14.5	4
	Distance between CF frames	3059.7	19.7	1
	Frame material	1480.5	9.5	6
	Jointing method between CF frames	2450.7	15.8	3
Climbing hydraulic robot	Shape of hydraulic robot	1580.4	18.9	2
	Distance between hydraulic robots	526.8	6.3	8
	Number of hydraulic robots	2100.6	25.2	1
	Oil pressure of hydraulic robots	1480.5	17.8	3
	Jointing method with CF	769.1	9.2	4
	Number of joints	700.2	8.4	5
	Flow control method	562.4	6.7	7
	Size of power source	620.1	7.4	6
Core wall	Location of core hall	700.2	43.3	2
	Concrete strength of external wall	917.5	56.7	1

4. FINDINGS AND DISCUSSIONS

To develop appropriate design components for the RCA system, researchers should firstly recognize how important the different qualities are for each component and what technical characteristics are necessary to meet these qualities. However, at the early stage of studying this system, the participants had difficulties with lack of communication and knowledge concerning other research domains.

The QFD approach has effectively identified the important needs and relevant design elements, and also offered the priorities of technical factors satisfying the design characteristics of the robot-based construction automation system. In addition, QFD produces quantitative importance and design priorities for the technical factors, which assists in designing an efficient construction process.

In the results of the questionnaire survey, the elements regarding robust and precise bolting operation are described as important demands because fitting bolts and joining and turning nuts are extremely difficult tasks for a robot. For instance, the items marked ② in steel frames and joints and in the CF may support robust and precise bolting operations efficiently. Thus, the mutual interaction of different components is important for accomplishing the bolting operation successfully. These demands are highly correlated with technical factors: robot shape, sensing and remote-control devices and the anchoring device in the robotic crane, joint shape and bracket length in the steel frame and joint, and distance between CF frames in the CF.

5. CONCLUSIONS

The robot-based construction automation (RCA) system will be an effective approach to overcoming the lack of skilled labor and to ensuring competitiveness. Consequently, there has been much development of construction robots and core technologies related to robot control and manipulation. Design for Automation (DFA) should be conducted in parallel with core technologies to improve the efficiency of the RCA system.

This study has presented the components design process in the RCA system using the QFD approach. From this process, the researchers' needs are identified, and the priorities of their technical requirements are derived. These results help the developers to focus on the important design quality factors of each component. As a result, this study contributes to providing the appropriate design of each component that satisfies the developer's requirements and that can be used as a guide for the further study of construction automation in the future. This study should be elaborated to allow its universal application, and technical requirements should be subsequently translated into more specific design characteristics.

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