Scientia Iranica A (2019) 26(6), 3085–3096

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
http://scientiairanica.sharif.edu

Systematic approach to the design of modular military housing units using six-sigma

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Received 16 October 2016; accepted 27 January 2018

KEYWORDS
Six-Sigma;
Modular construction;
Quality function deployment;
Military housing unit;
Steel structure.

Abstract. Military quarters and barracks are representative of housing units where the same plan is repeated and, thus, prefabricated housing production can be effectively applied. These housing units are required to be disassembled and recycled as military forces are frequently reorganized and deployed to perform military actions. In order to meet these needs, this study proposes a systematic approach to the design of modular military housing units based on Six-Sigma concept. The application of Six-Sigma to modular military housing units allows customers' needs to be reflected on the critical-to-quality parameter, which summarizes the main design requirements. In addition, the design concept of the modular units can be developed based on the derived critical-to-quality functionalities. To evaluate the effectiveness of the proposed approach, a representative example of military housing units is chosen and designed by utilizing the new modular units developed through this procedure. The weight of frames per unit area and factory manufacturing ratio of the new design are analyzed. The results of the comparison show that the use of the new modular units not only reduces construction cost significantly, but also greatly improves the quality of construction.

1. Introduction

Modular construction can be defined as a three-dimensional volumetric unit that can be manufactured in a factory, delivered to the construction site, and assembled as the main structural elements of the building [1]. It has been widely applied to many different types of building construction in Europe and Japan. In Korea, it has been applied mainly to school buildings and military facilities [2].

Military barracks and Bachelor Officers' Quarters (BOQs) are representative housing units that use the same plan repeatedly, which makes them good candidates for prefabricated housing production. These housing units must be disassembled and recycled because military forces are frequently reorganized and deployed to various locations. In Korea, the military owns 100,000 buildings nationwide in a total area of 25.2 million m^2; however, approximately 30% of the building facilities are more than 20 years old. Therefore, new construction methods are required to improve the quality of military facilities. For this purpose, modular construction has been applied in Korea to

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doi: 10.24200/sci.2018.20162

(a) Platoon military barrack (b) Battalion barrack (c) Military office

Figure 1. Modular military facilities in Korea.

the construction of platoon barracks, military offices, battalion barracks, and BOQs, as shown in Figure 1. In the process of applying modular construction to military facilities, the important factors include cost reduction through the standardization of construction units and reusability of the construction elements that are disassembled at the end of their useful life. Most existing military modular construction facilities in Korea fail to meet those requirements [3].

In order to address this issue, this study develops new military housing units based on the so-called Six-Sigma methodology [4]. The Six-Sigma was first developed by Motorola in the 1980s [5] and became well-known in the 1990s when Jack Welch applied it to develop strategies for his company, General Electric. The application of the Six-Sigma to modular military housing units allows customers' needs to be reflected on the critical to quality, which summarizes the main design requirements. The design concept of the modular units can be developed based on the Critical To Qualities (CTQs). To evaluate the effectiveness of the proposed approach, a representative example of military quarters is chosen and designed by utilizing both the new modular units developed through this procedure and existing modular units. The frame mass per unit area and prefabrication ratio of the two cases are compared and analyzed.

2. Derivation of CTQ for modular military housing

In order to derive the requirements for modular military housing units, potential customers are grouped into one of the two following categories: external and internal customers. The former consists of design firms, module manufacturers, and contractors; the latter includes owners and residents. The requirements of the two customer groups for the modular military housing are listed in Table 1, which summarizes the results of customer interviews. In the table, "raw data", which are also called the voice of customers, represent the customers' opinions on existing military modular units, and "required quality" represents the quality of the product required to reflect the customers' opinions. The required quality derived from the Voice Of Customer (VOC) in the interviews can be converted to quality characteristics for design through the House Of Quality (HOQ) structure, as illustrated in Figure 2. The HOQ organizes items based on the required qualities given in Table 1. The importance and satisfaction of each item are assessed through a survey of customers.

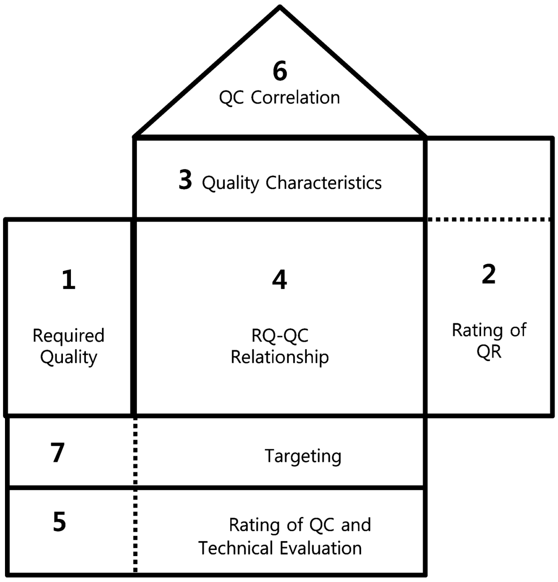


Figure 2. House of quality for quality function deployment analysis.

Figure 3 shows the importance and satisfaction evaluation of the customers' requirements. The items of "short construction period", "easy to disassemble", "compatible to other modules", and "low construction cost" are considered to be highly important; however, the evaluation of the performance of the existing system regarding these items receives low ratings. Based on these results, Table 2 provides the priority rating on the customers' required qualities. Based on the results of the table, items with high priority are found to include "easy to disassemble", "reduction of construction cost", and "shortening of construction time period."

This study uses the Quality Function Deployment

Table 1. Requirements of potential customer groups.

Customers	Voice of customer (raw data)	Scene Who, where, when	Required quality
Architect	Poor exterior design	Architects design modular buildings using the developed modules	Introduction of various exterior designs
Module manufacturer	Using too many kinds of materials	Manufacturers reserve key materials for modules in stock at the factory	Using standard materials
	Difficult to deliver modules. High cost for delivery	Manufacturers deliver modules to the construction site	Easy delivery of modules
Contractor	Damage occurring during delivery and installation of modules	Contractors install modules at construction site	Safe for rainfall and minimized damages during delivery
Owner	Higher construction cost than that of conventional methods	The owner compares the costs of traditional and modular construction methods	Low construction cost
	Not easy to reuse	The owner disassembles modules to deploy military forces after using them many years	Easy to disassemble and deliver
User	Poor residential performance of existing modular buildings	Residents stay in the housing after work	Excellent thermal, optical, and sound performances

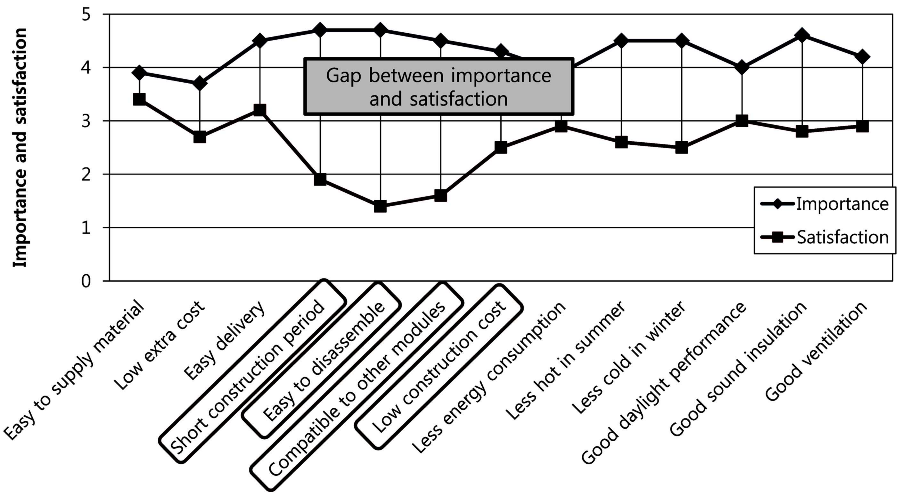


Figure 3. Importance and satisfaction evaluation of the customer's requirements.

(QFD) methodology to convert customers' required qualities into the quality characteristics of the products to be developed. The QFD methodology is a tool that can make a quantitative evaluation of the relation between the customer required qualities and product characteristics using a correlation matrix [6]. The results of the analysis using the correlation matrix are provided in Table 3. Based on the correlation analysis, parameters that are critical to quality from the customers' perspective can be

Table 2. Priority rating of the customers' required qualities.

Customers' required quality	(1) Importance rating	(2) Satisfaction rating	(3) Possible quality levels	(4) Level-up ratio	(5) Sales Point	(6) Absolute priority	Priority ratio (%)	Rating
Easy to supply material	3.9	3.4	5	1.5	–	5.8	5.4	6
Less extra cost	3.7	2.7	3	1.1	–	4.0	3.7	11
Easy delivery	4.5	3.2	5	1.6	◎	10.7	9.9	4
Short construction period	4.7	1.9	5	2.7	–	12.7	11.8	3
Easy to disassemble	4.7	1.4	5	3.5	◎	24.7	23.0	1
Compatible to other modules	4.5	1.6	3	1.9	○	10.2	9.5	5
Less construction cost	4.3	2.5	5	2.0	◎	12.9	12.0	2
Less energy consumption	3.9	2.9	2	1.0	–	3.9	3.6	13
Less hot in summer	4.5	2.6	2	1.0	–	4.5	4.2	9
Less cold in winter	4.5	2.5	3	1.2	–	5.4	5.0	7
Good daylight performance	4.0	3.0	2	1.0	–	4.0	3.7	11
Good sound insulation	4.6	2.8	2	1.0	–	4.6	4.3	8
Good ventilation	4.2	2.9	2	1.0	–	4.2	3.9	10

(1) Importance rating: Values obtained from customer survey ($1 \sim 5$);

(2) Satisfaction rating: Values obtained from customer survey ($1 \sim 5$);

(3) Possible quality levels from a viewpoint of developers ($1 \sim 5$);

(4) Level-up ratio: (3)/(2);

(5) Sales point from a viewpoint of developers (◎: 1.5, ○: 1.2, no symbol: 1.0);

(6) Absolute priority: (1) × (4) × (5).

derived. Among 11 quality characteristics in the table, the top 6 are selected as the parameters Critical To Quality (CTQs) and used to set up development targets.

Next, the development targets can be set by analyzing the current levels of the potential CTQs in Table 3 and performing a benchmarking analysis. The benchmark target of this study is set by referring to a military modular system developed by a UK-based company, Corus Living Solutions (CLS) [7]. The target levels of the potential CTQs are summarized in Table 4. Among them, "no. of module types", "no. of types of structural members", and "no. of connections during on-site construction" are difficult to quantify consistently, and "module length" does not contribute significantly to module improvement. Therefore, "factory manufacturing ratio" and "weight of frames per unit area" are chosen as the final CTQs.

3. Derivation of design concepts

Based on the selected CTQs in the previous section, key functions are derived to design a new modular military housing unit. A correlation analysis between the quality characteristics and key functions is performed, as shown in Table 5. The results of the analysis indicate that highly prioritized functions include "connecting exterior panels", "connecting plumbing pipes", "waterproofing during delivery", "connecting corridor panels", and "loading on trailer".

Table 6 shows possible solutions for each key function. For instance, three solutions are available for the required functions of "connecting exterior panels" and "connecting corridor panels." Possible design concepts can be developed by combining the available solutions for each key function. An example of a design concept obtained by a combination of solutions

Table 3. Correlation analysis between customers' required qualities and quality characteristics.

Customers' required quality	Quality characteristic: Weight	Reusability		Standardization		Dimension of modules			Residential performance			Absolute priority	Priority ratio (%)	Rating
	Weight of frames per unit area	Factory manufacturing ratio	Number of connections during construction at site	Number of types of structural members	Number of module types	Module height	Module length	Module width	Window area ratio	Sound insulation	Thermal insulation			
Easy to supply material	–	–	–	◎	○	–	–	–	–	–	–	5.8	5.4	6
Low extra cost	○	○	–	○	◎	–	–	–	–	–	–	4.0	3.7	11
Easy delivery	○	–	–	–	–	○	◎	○	–	–	–	10.7	9.9	4
Short construction period	–	◎	◎	–	△	–	–	–	–	–	–	12.7	11.8	3
Easy to disassemble	–	◎	◎	–	△	–	–	–	–	–	–	24.7	23.0	1
Compatible to other modules	–	–	–	–	◎	–	–	–	–	–	–	10.2	9.5	5
Low construction cost	◎	–	–	◎	–	○	○	○	–	–	–	–12.9	12.0	2
Low energy consumption	–	–	–	–	–	–	–	–	○	–	◎	3.9	3.6	13
Less hot in summer	–	–	–	–	–	–	–	–	○	–	◎	4.5	4.2	9
Less cold in winter	–	–	–	–	–	–	–	–	○	–	◎	5.4	5.0	7
Good daylight performance	–	–	–	–	–	○	–	–	◎	–	–	4.0	3.7	11
Good sound insulation	–	–	–	–	–	–	–	–	–	◎	–	4.6	4.3	8
Good ventilation	–	–	–	–	–	○	–	–	◎	–	–	4.2	3.9	10
Absolute priority	160	349	337	180	183	95	135	71	115	41	124	–	100	–
Priority ratios (%)	8.9	19.5	18.8	10.1	10.2	5.3	7.5	4.0	6.4	2.3	6.9	–	–	–
Ratings	5	1	2	4	3	9	6	10	8	11	7	–	–	–

Table 4. Target levels of the potential CTQs.

Potential CTQs	Factory manufacturing ratio	No. of connections during construction on site	No. of module types	No. of types of structural members	Weight of frames per unit area	Module length
CTQ priority ratio (%)	19.5	18.8	10.2	10.1	8.95	7.54
Default level	42%	0.15 per m^2	5	6	0.76 kN/m^2	6 m
Target level	70%	0.1 per m^2	4	3	0.59 kN/m^2	6 m

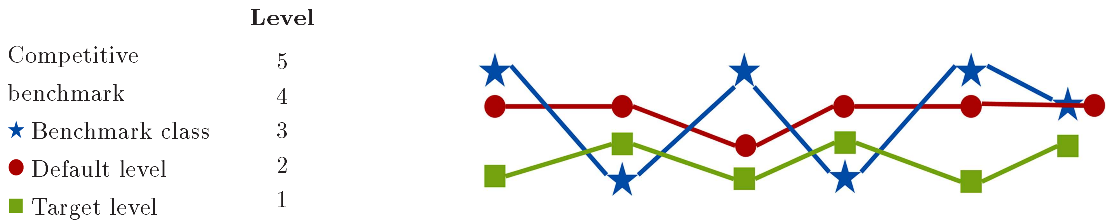


Table 5. Correlation between the quality characteristics and key functions.

Quality characteristics	Key functions																
	Delivery		Assembly of modules								Performance of modules						
	Waterproofing during delivery	Loading on trailer	Passing under viaduct	Lifting modules	Locating modules	Connecting corridor panels	Connecting plumbing pipes	Connecting electric pipes	Connecting interior panels	Connecting exterior panels	Resisting vertical loads	Resisting horizontal loads	Waterproofing	Sound insulation	Thermal insulation	Fireproofing	Drainage
Factory manufacturing ratio	◎	○	–	–	–	○	◎	○	○	◎	–	–	○	–	–	–	–
Number of connections at site	○	–	–	–	–	◎	◎	○	–	◎	–	○	–	–	–	○	–
Number of kinds of modules	–	–	–	–	○	–	–	–	–	–	○	–	–	–	–	–	–
Number of kinds of structural members	–	–	–	◎	–	–	–	–	–	–	–	–	–	–	–	–	–
Weight of frames per unit area	–	◎	–	◎	○	–	–	–	–	–	○	○	–	–	–	–	–
Module length	–	–	–	–	–	–	–	–	–	–	–	–	–	○	○	–	–
Thermal insulation	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Window area ratio	–	–	–	–	–	–	–	–	–	○	–	–	–	–	◎	–	–
Module height	–	–	◎	–	–	–	–	–	–	–	–	–	–	–	–	–	○
Module width	–	◎	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sound insulation	–	–	–	–	–	–	–	–	–	–	–	–	–	◎	–	–	–
Priority ratio (%)	10.6	8.0	2.2	7.8	2.6	10.4	15.7	5.2	2.7	16.6	2.6	3.8	2.7	2.0	3.7	2.6	0.7
Rating	3	5	15	6	12	4	2	7	10	1	12	8	10	16	9	14	17

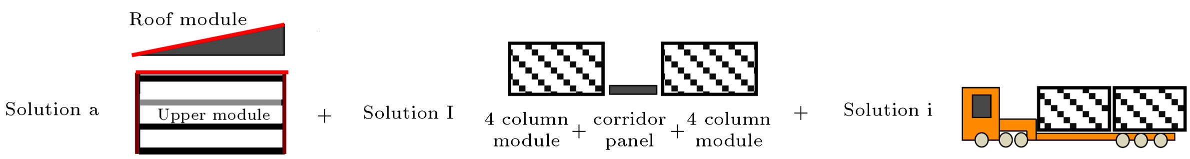


Figure 4. An example of a design concept obtained by a combination of solutions.

is shown in Figure 4. A total of five design concepts are derived by following this procedure. A Pugh matrix is created to select the optimal design among the candidates listed in Table 7. In this table, a relative evaluation of each candidate is carried out by comparing it with the design of the existing modular system for each of the key criteria. The results of the table indicate that the design concept (2) is the optimal one. Thus, it is selected as the final design of the new military modular housing unit.

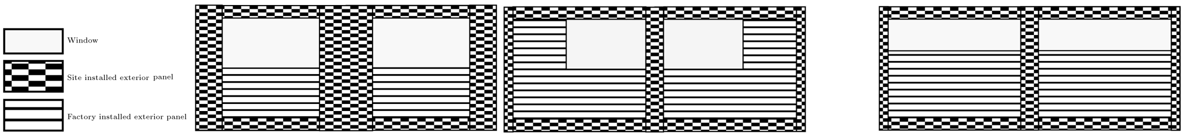
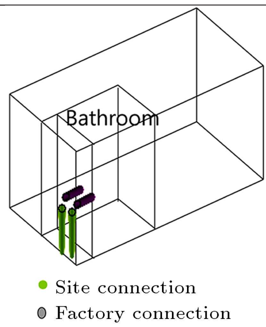
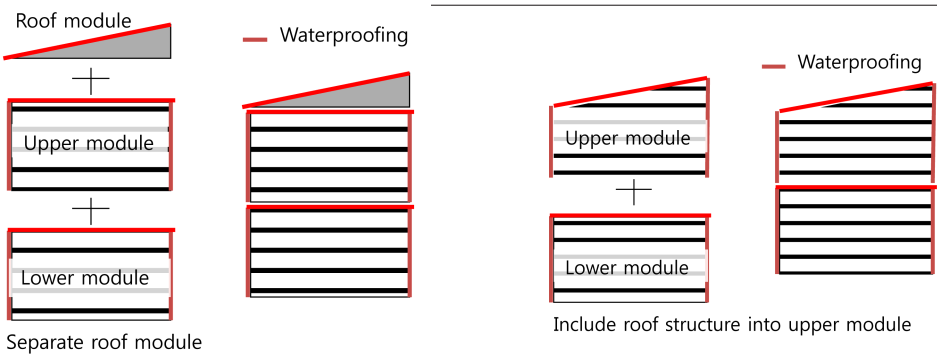
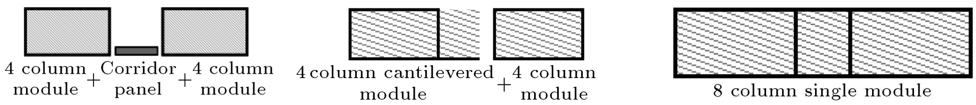
4. Detailed design and design verification

4.1. Detailed design

In this section, a detailed design is created based on the concept derived from the previous section. Figure 5 shows the plan of a representative example of Reinforced Concrete (RC) military housing units in Korea. The developed modular design concept is applied to the design of this representative example.

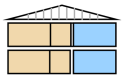
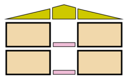
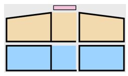
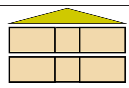
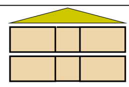
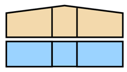
The military housing unit for a single person is

Table 6. Possible solutions for each key function.

Key functions	Solution		
Connecting exterior panels	Sol. 1 Locating windows at the center of module front	Sol. 2 Locating windows at the side of module front	Sol. 3 Using wide windows
			
Connecting plumbing pipes	Sol. A: Installing a pipe shaft at the corridor side. Including horizontal pipes inside the module and connecting vertical pipes at the site		
Waterproofing during delivery	Sol. a: Making a separate roof module and installing waterproofing sheet on top of the module.		Sol. b: Including a roof structure on the top floor module.
			
Connecting corridor panels	Sol. I: Making a separate corridor panel.	Sol. II: Making a cantilevered corridor module.	Sol. III: Making a long module including corridor.
			
Loading on trailer	Sol. i: Delivering two modules at a time.		Sol ii: Delivering one module at a time.
			

designed to have the same size similar to the factory-built module with a width of 3.3 m. Windows and pipe shafts are included in the unit to maximize the factory manufacturing ratio. Table 8 presents the results of a detailed unit room design. The cross-sectional details of the representative example are given in Table 9. The sloped roof frame is integrated into top story units to minimize the weight of frames per unit area while increasing the factory manufacturing ratio. The detailed frame design of the representative example is

Table 7. Derivation of the final design concept using a Pugh matrix.

Design concept		Default	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Key criterion	**Weight**						
Frame cost	5	S	S	+	S	S	+
Easy delivery	3	S	+	+	+	–	–
Reusability	5	S	S	+	–	+	+
Site construction time	3	S	–	+	–	+	+
Military design guide	4	S	S	S	+	+	–
Manufacturing cost	4	S	+	–	S	–	–
Compatibility	4	S	+	–	S	+	S
Creativity	2	S	S	+	+	S	S
Sum of positives		0	3	5	3	4	3
Sum of negatives		0	1	2	2	2	3
Sum of the sames		8	4	1	3	2	2
Weighted sum of positives		0	12	18	10	16	12
Weighted sum of negatives		0	–3	–8	–7	–8	–12

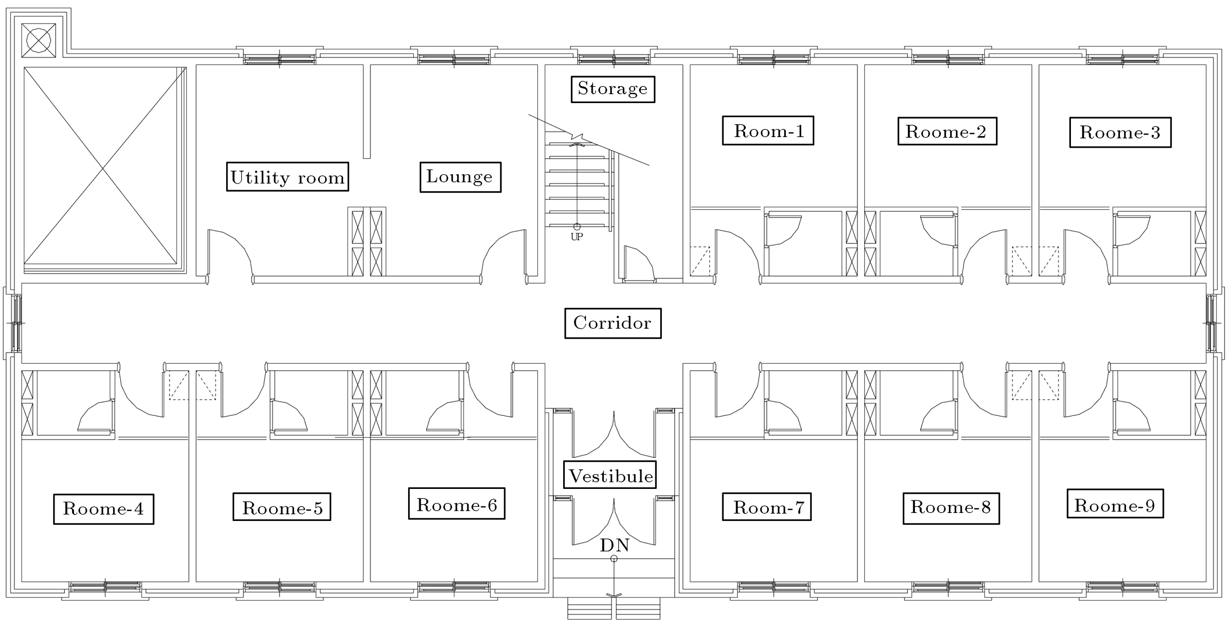
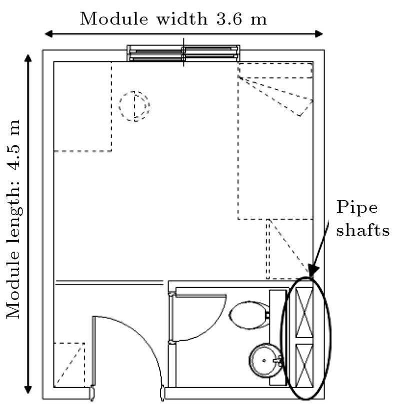
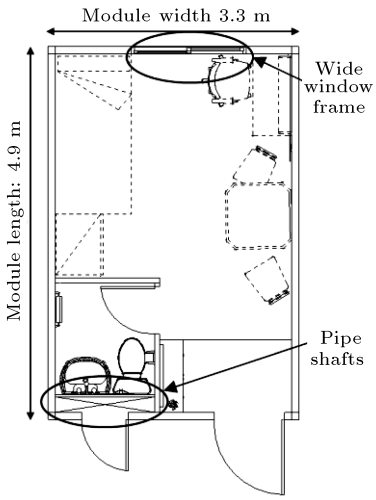


Figure 5. Plan of a representative example of RC military housing units.

illustrated in Table 10. As shown in the table, four types of unit frames are assembled to form a single frame unit, and the double-sided corridor is attached on the side of the module in the form of a cantilever. In addition, duplicated column sections are eliminated to optimize the design of frame modules. Figure 6 shows the plan and bird's-eye view of the final design of the representative military housing units, which has 20 modular unit rooms and is constructed by combining totally 29 modular units.

Table 8. Detailed unit room design of the representative example.

<table>
<tr><td>Key function considered</td><td colspan="2">Connecting exterior panels
Connecting plumbing pipes</td></tr>
<tr><td>Design factor</td><td colspan="2">Design of a unit module plan</td></tr>
<tr><td>Definition</td><td colspan="2">Design of a unit module for a single person</td></tr>
<tr><td colspan="2">As is</td><td>To be</td></tr>
<tr><td colspan="2">- Unit plan based on RC frames: width of 3.6 m × length of 4.5 m = 16.2 m^2
- Pipe shafts located on the wall side between two units


Plan of RC BOQ</td><td>- Determining width and length considering easy delivery: width of 3.3 m× length of 4.9 m = 16.17 m^2
- Pipe shafts located on the corridor side of the bathroom


Plan of modular BOQ</td></tr>
<tr><td>Design point</td><td colspan="2">- Determine the width and length suitable for easy delivery
- Design pipe shafts to maximize the factory manufacturing ratio</td></tr>
<tr><td>Expected effects</td><td colspan="2">Satisfy the military design criteria</td></tr>
<tr><td>Results</td><td colspan="2">Plan the drawing of a unit room</td></tr>
</table>

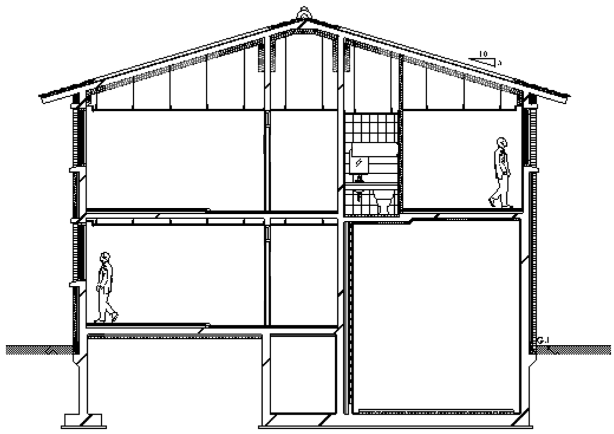
4.2. Design verification

In this section, a design verification of the final product of the military housing units developed in the previous section is performed. The adequacy of the developed system is investigated by evaluating the achievement of the target levels of the two final CTQs listed in Table 4. The results of the verification are summarized in Table 11.

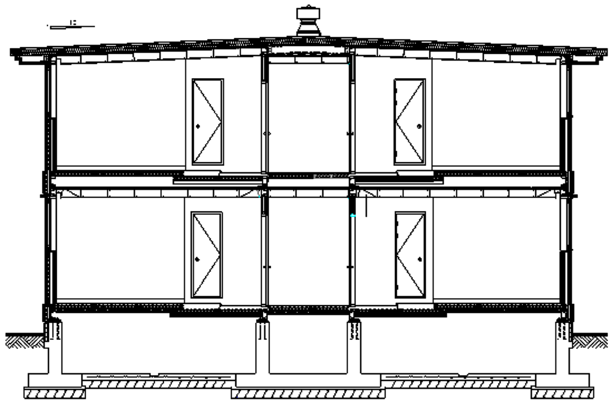
The achievement level of the first CTQ, which is the factory manufacturing ratio, is assessed based on the ratio of manufacturing cost to the total construction cost excluding foundation and transportation. The results of the table indicate that the factory manufacturing ratio of the final product is 75.2%. Considering that the corresponding value of the existing modular military housing units is 42.9%, it is almost 80% improvement and exceeds the target value, which is 70%. This is possible mainly because most of the piping lines and internal finishing are manufactured in the factory, thus resulting in better product quality. The weight of frames per unit area of the developed modular system, which is the second CTQ, is 0.60 kN/m^2, which is also greater than the target value, 0.59 kN/m^2. This is only 62% of the corresponding value of the existing modular system. Consequently, the results of the comparison show that the use of the new modular

Table 9. Detailed cross-sectional design of the representative example.

Key function considered	- Connecting exterior panels. - Connecting plumbing pipes.
Design factor	Design of a cross-section.
Definition	Design of a cross-section of the representative example.
As is	To be
- RC frame unit plan. - Ceiling height: 2.4 m - Roof slope: 3/10.	- Sloped roof with 1/10 slope. - Ensure at least the ceiling height of 2.4 m. Average ceiling height of top story is higher than 2.4 m. - Horizontal pipes are located at the ceiling of corridor. - Vertical pipes are connected at the underground pit.



Section of RC BOQ

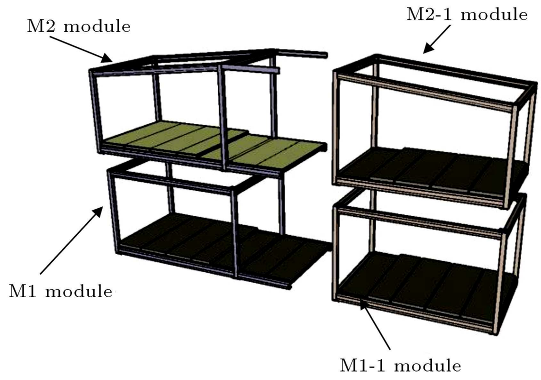


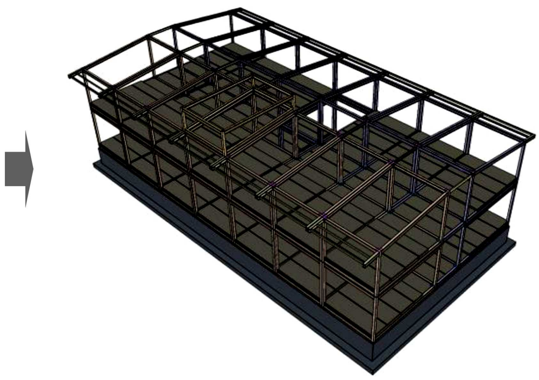
Section of RC BOQ

Design point	Minimizing module height while satisfying the military design criteria.
Expected effects	Enhanced cost-effectiveness due to reduced story height.
Results	Planning the drawing of a unit room.

Table 10. Detailed frame design of the representative example.

Key functions considered	Connecting corridor panels Loading on trailer
Design factor	Design of frames
Definition	Design of frames of the representative example
To be	
- Using four different modules - Using roof-structure integrated modules - Using cantilevered corridor modules - Delivering two modules at a time	





Design point	Optimizing frame composition using four different modules
Expected effects	Minimizing the weight of frames per unit area
Results	Structural drawings for four different types of modules

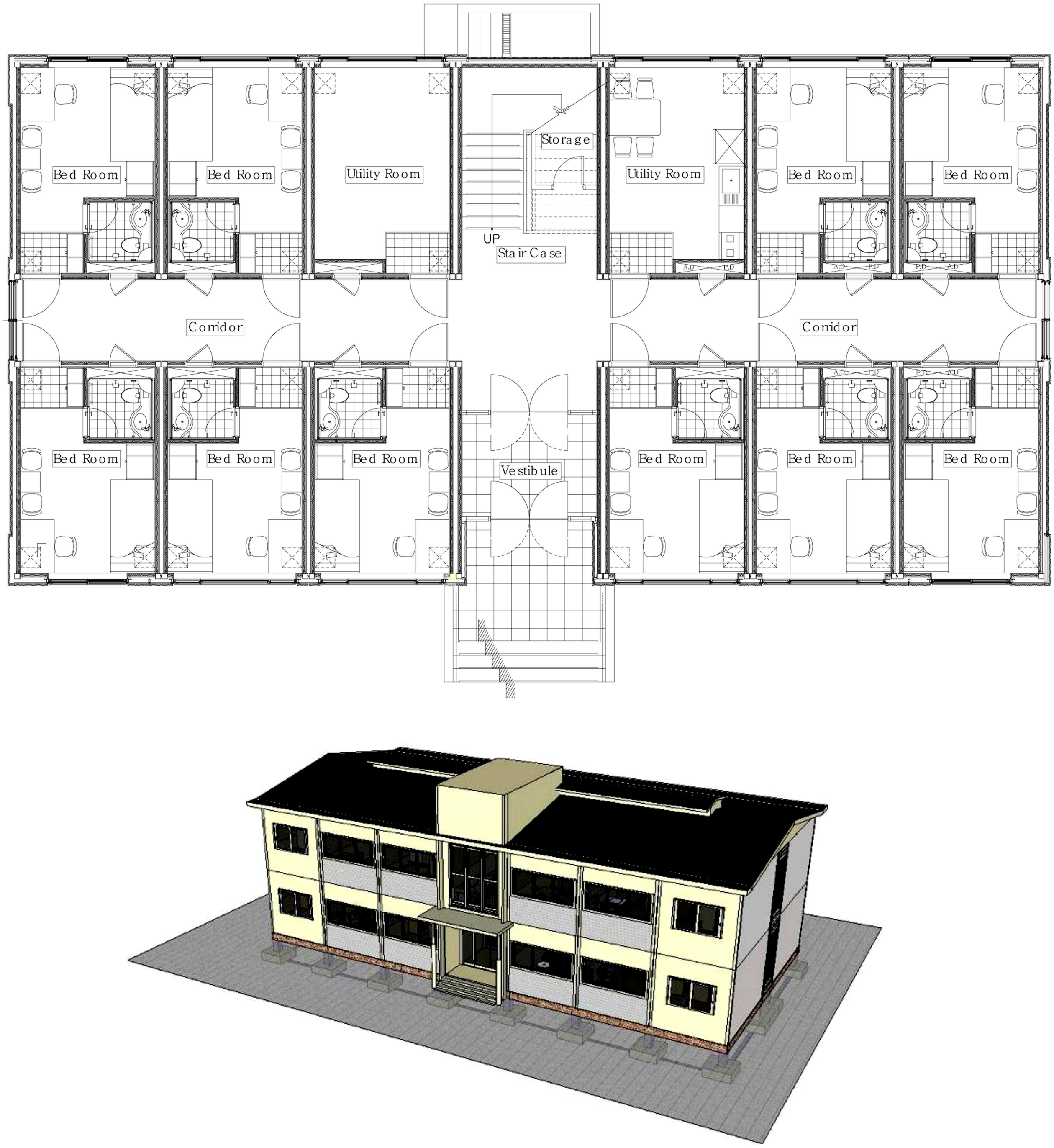


Figure 6. Plan and bird's-eye view of the newly designed military housing units.

Table 11. Verification of the designed final product.

CTQs	Verification method	Target value	Design result
Factory manufacturing ratio	Ratio of manufacturing cost to the total construction cost excluding foundation and transportation	70%	75.2%
Weight of frames per unit area	Weight of steel frames divided by floor area	0.59 kN/m^2	0.60 kN/m^2

units not only reduces construction cost significantly, but also greatly improves the quality of construction.

5. Concluding remarks

This study proposed a systematic approach to the design of modular military housing units based on Six-Sigma concept. The application of the Six-Sigma to modular military housing units allows customers' needs to be reflected on the CTQ, which summarizes the main design requirements, and the design concept of the modular units can be developed based on the derived CTQs. To evaluate the effectiveness of the proposed approach, a representative example of military housing units was chosen and designed by utilizing the new modular units developed through this procedure. The weight of frames per unit area and the factory manufacturing ratio of the new design were analyzed. If compared to the existing modular system, the former is improved by 80%, and the latter is reduced by 62%. This indicates that the use of the new modular units not only reduces construction cost significantly, but also greatly improves the quality of construction.

Acknowledgement

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (Ministry of Science, ICT & Future Planning) (No. 2017R1A2B4004729).

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