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A new approach for optimal design of intensive care unit

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Abstract

Planning and budgeting for healthcare facilities necessitate precise estimation and a thoughtful analysis of the required area for each department, as well as extensive knowledge of the most important elements that can influence the design and provide an appropriate environment for staff and patients. A gross conversion factor is influential in calculating the entire area of a department. However, there is no precise standard indicating how this factor should be calculated. To address this problem, quality function deployment (QFD) has been implemented. The intensive care unit (ICU) is one of the highly equipped departments that should be properly planned; therefore, it was selected for application. The five steps of the QFD are used to identify and rank the most important and efficient design features. Only the top factors are considered in calculating the required area for the ICU department. This approach presents a unique method for estimating the gross square area based on calculating the gross conversion factor. To demonstrate the proposed approach's efficacy, it was applied to two Egyptian public hospitals. The results reveal that 15–16% of the total space of both hospitals can be reduced from the total department space. Moreover, an outstanding reduction in ICU design and preparation expenses has been achieved. The design reduces the required budget for a project while maintaining the same construction material quality and accommodating extra beds. Additionally, the QFD proves its ability to redesign the ICU department while reducing costs.

Keywords: Hospital planning, Hospital design, Gross factor, ICU, Quality function deployment

Introduction

Healthcare facility design is a process that demands a good knowledge of hospital design standards and adequate experience in planning. According to the California Healthcare Foundation guidelines, the planning process is divided into three phases: project definition and planning, design and documentation, and finally building and license [1]. Planning is the most vital phase in which the whole project is analyzed in terms of the hospital mission, number of served patients, treatment strategies, determined spaces, workflows, and project costs [2]. This process includes the most essential elements, which highly affect the total project life cycle and the required spaces as well.

Indeed, the planning of healthcare facilities does not adhere to the same rules as other buildings' planning and construction processes. It has regular standards that must be followed during the design and construction. It should deliver an appropriate environment that influences the patient treatment life cycle as well as controls the infection rate within hospitals. In fact, healthcare facility construction is predicted to exceed $250 billion in the coming decade [1]. Therefore, it requires good knowledge and best practices in the planning process. One type of optimal planning is calculating appropriate spaces for various departments, particularly key departments such as the intensive care unit (ICU) where seriously ill patients are cared for.

Thus, the planning process for the ICU department must follow regular guidelines in terms of location, design, size, and environment. In general, ICU design and size are highly regarded by hospital designers. Therefore, estimating the entire spaces in the ICU should follow a sequential procedure. In practice, there are two terms used in hospital planning and design to propose the departmental workload: gross square feet and net square feet [1]. According to the USA Department of Defense (DoD) [3], "Net Square Feet (NSF) is the area of an individual room or the usable floor area that is assigned to a function in an open area." A room's net square footage is determined by taking the outer boundaries of the floor in an open space and the interior finished surface of any surrounding walls or other enclosing components. This excludes other spaces, such as columns, stairs, and circulation areas. The department gross square feet (DGSF) is identified as "a measurement of an assemblage of rooms and spaces as assigned to a department or service and includes internal departmental and/or service circulation and partitions, columns, and projections enclosing the structural elements of the building within the departmental space." Depending on the DGSF, the Building Gross Square Feet (BGSF) is determined by aggregating all DGSFs in addition to the walls, the structures, the stairs, the elevators, and any other area comprising the entire building.

In general, the departmental gross square feet or area (DGSA) is calculated by multiplying the departmental net square feet or area (DNSA) by a factor called the gross conversion factor. Therefore, the gross conversion factor or gross factor for a department is a ratio between the DGSA and the DNSA. This ratio is used to estimate the amount of unusable space needed to organize the net spaces within the department [1]. Additionally, the judgement of experts who are familiar with the ICU departments is required to estimate this factor.

According to the previous related works, there is no prior method to determine the gross conversion factor or even to give a guide on how to calculate it. Furthermore, there is no established method for identifying the most influential factors, necessitating their initial determination. It is worth mentioning that the DoD provides guidelines for departmental gross factors based on the function of a department in addition to building gross factors based on the size of the hospital [3]. Thus, this study aims to develop a novel method for determining the gross factor.

We propose quality function deployment (QFD) due to its reliability in planning issues [4]. The results led to identification of the most essential criteria. Next, we determined the gross conversion factor. To demonstrate its effectiveness, the method was implemented in the ICU departments of two hospitals. The new gross factor (GF) and the gross areas were estimated. Additionally, the approximately needed budget was compared before and after the methodology's implementation.

This research will be such a useful reference for the planning or modification of the ICU, and it could be applied to the whole hospital for obtaining accurate space estimation. Also, it adheres to the affected budgeting plan by following the same standards, using the same quality of finishing materials, and serving the same number of patient beds. Most planners use the GF values that are defined by the US standards because there is no exact way to calculate them [1]. A group of American healthcare organizations has released a study that addresses methodologies for estimating the project space and how they could affect the calculated ratios [5]. Therefore, the study recommended that the design and planning of healthcare facilities need an accurate and standardized method for calculating the GF [1]. As a result, the problem we attempt to solve is how to calculate the GF using a standardized method to estimate the gross area. The contributions of the study are summarized as follows: (1) developing a new method for calculating the GF; (2) estimating the appropriate gross area required for the ICU; (3) using the QFD as a methodology for GF calculation; (4) saving costs for furnishing the ICU; and (5) providing a guideline for optimal planning and design of healthcare facilities.

Related works

Performing planning and budgeting for the healthcare facility needs precise estimation and a thoughtful analysis of the required area for each department. Identifying influential elements for appropriate design of the facility is essential. They affect the safety of patients and medical staff in addition to the hospital environment. A real challenge of healthcare facility design is to select an appropriate standard (codes) that adapts with the requirements of each department. Indeed, these standards lead to control of the infection and affect the quality level of diagnosis, therapy, and treatment. Obviously, this is not only affecting the patient but also affecting the working staff as they are highly involved in all phases of the healthcare delivery system.

Generally, the medical planning process is divided into three phases: project definition and planning, project design and documentation, and finally building, license, and evaluation. Each phase encompasses many processes for implementation [1]. Phase two is considered the biggest one since it involves various processes with many stakeholders. In another context, the World Health Organization (WHO) has published a guideline for the construction of healthcare facilities [6]. Additionally, the WHO declares three interdependent items that should be regarded in the design process: health service delivery system, environment, and community.

Tronstad et al. [7] proposed a pertinent study to redesign an ICU with a patient-centered design in mind. The study has discussed how a complex environment can negatively affect bed spacing in the ICU. The authors outlined a hybrid module to tackle this problem. Contributors to the complicated environment were measured and included noise, lighting, alarms, and acoustics. A list of issues that were patient-centered was recognized in addition to those that had already been identified. These solutions include IT service improvement, architecture design, and other administrative aspects.

Another study has discussed the consideration of patient safety during the early planning of a hospital. The author has adopted an integrated method using the QFD and logical framework approach (LFA) to improve patient safety in hospital design. The role of QFD is to identify and prioritize a set of criteria that could impact on patient safety. LFA is used to develop a project plan that measures the progress of hospital design implementation through its life [4]. The methodology was applied on the emergency department (ED).

Abdel Samad et al. [8] published a study in 2018 focused on how to redesign the ED. The idea was to collect the requirements of the stakeholders and compare them with specific standards. The QFD was employed to make a comparison between them. According to a study of the survey responses, there were some inconsistencies between stakeholder demands and the current designs. The results revealed the positive impact of considering stakeholder requirements in designing the ED. Another study considered the ICU design with respect to noise [9]. An active noise control system has been designed to interface with noises around the patient bed by measuring this noise and reducing it. In a separate study, the public was invited to comment on whether there is a link between ICU architecture design and mortality rate [10]. The study assumed a correlation between the clinical outcomes, including the mortality rate, and the layout design of the ICU in one hospital. The results showed that putting seriously ill patients in ICU rooms that nursing personnel and doctors do not fully understand may result in increased mortality rates.

As such, despite the existence of hospital design guidelines, almost all related works consider the design of departments based on a given area. Based on our best knowledge, no article discusses how to estimate the optimal area required for a department's design. The aim was to improve the design with respect to patient safety and ergonomics for the staff by considering space layout in an optimal way. Moreover, the QFD method has been implemented in different scenarios for improving the design of ED. As a result, the authors decided to use this method to improve the ICU design based on the calculated required area.

Methods

The study aims to improve the design of the ICU department by developing a methodology to calculate the gross conversion factor. According to our best knowledge, there is no prior article that tackled the design of the ICU based on calculating this factor. Because of its consistency in hospital design, the QFD method is proposed to identify the influential criteria by considering the requirements of the stakeholders. Subsequently, by considering these factors, a new equation is developed to determine the GF. The principles of the QFD establishment are covered in the following sub-sections.

Quality function deployment

The concept of quality function deployment (QFD) was originated in Japan in the 1960s by Yoji Akao. The purpose was to improve a product design launched by Mitsubishi Heavy Industries [11, 12]. The QFD encompasses four stages, the first one is called "house of quality" or (HoQ). It is designed to convert the customer requirements (WHATs) into engineering or technical requirements (HOWs) that may be used in a variety of contexts to satisfy customers. Six steps are taken to establish the HoQ: customer needs identification, technical need identification, relationship between them, WHATs rate importance, HOWs correlation, and HOWs rate importance [13]. More information on the HoQ establishment can be found in literature [11, 13, 14]. Because the HoQ is a customer-focused tool, it is critical to identify the customers with whom we are concerned. In this instance, in addition to the patients and their families, the customer also comprises the medical staff, including doctors, nurses, coordinators, and technicians.

Customer requirements identification

A survey was conducted to identify the customer need for optimal ICU design. According to the customer category, the requirements are divided into doctors, nurses, patients and their families, and services, as depicted in Table 1. The survey had 39 questions, and answers were taken on a scale of 1 to 5. As a result, 40 clauses were driven by customer requirements. To this point, according to the given scales of answers, priority was given to the questions, which in turn yielded the 40 requirements. The requirements for nursing staff are the most prevalent of the 40 clauses, with 17 clauses.

Technical requirements identification

Identifying the voice of engineers or technical requirements depends on what customer requirements are provided. In our case study, three experts were involved in formulating the technical requirements for designing an optimal ICU department. An average of

Table 1 Customer requirements for the optimal design of an ICU department

Nurses	Physicians	Services	Patients and families
Quick services	Prepared pantry room	Prepared area for equipment	Clean and quite rooms
Easy patient transfer	Accessed computer	Store for cleaning utilities	Controlled room temperature
Direct contact with patient	Prepared diagnosis area	Closed area for infected control	Good ventilation
Sufficient working area	Training and education room		Prepared waiting area
Quick arrival of supplies	Area for meeting patient families		Patient surveillance
Safe environment	Prepared lounges		Easy arrival for patient rooms
Less noise level	Prepared offices		Easy admission procedure
Observation desk location	Improved circulation		Easy communication with staff
Communication with patient			Privacy
Staff separate toilets			Well-trained staff
Appropriate staff lounge			Safe environment
Hand washing stations			
Office location of nurse head			
Easy access to all room services			
Multi-observe to patients			
Prevent infection control			
Room preparation to treatment processes			

10 years of experience was a common factor. Additionally, the viewpoint of the survey's researcher was taken into account. Consequently, a total of 24 clauses that fall under the categories of design and infrastructure are suggested by the stakeholders and are listed in Table 2. The design class encompasses items related to unit location, corridor size, room specifications, finishes, area specifications, and following standards. The infrastructure class includes nine items: a nurse call system, a fire system, hand washing units, air conditioning units, a central station system, elevators, telephones, an access card system, and patient room preparation.

Customer and technical requirements relationship

The core sub-matrix of the HoQ is the relationship between customer requirements and technical requirements. According to literature, the numbers 9, 3, and 1 are set for strong, medium, and weak relations, respectively [11, 13, 14]. The scale depicts how each factor relates to the other. Due to the large number of customer requirements, only one example of the relationship between customer requirements and all technical requirements is shown in Fig. 1.

Planning sub-matrix

Customer requirements should be ranked based on their significance to achieving the customer satisfaction. The role of the planning sub-matrix is to prioritize these requirements by calculating their weights. To determine the customer requirement weight, several steps are taken. First, each customer requirement is rated on a scale of one to five to present an initial score (S), with five being the most important and one being the least important. The second step is to identify the goal score (G) on a scale of 5 for each customer requirement. The third step is to determine the improvement ratio (IR), as in (1). Finally, the absolute weight (W_c) is determined by multiplying the improvement ratio (IR) by the importance factor (IF), as in (2). The relative weight is the normalized value of the absolute weight [11, 15]. To demonstrate how to calculate the absolute weight,

Table 2 Technical requirements for the optimal design of an ICU department

Design	Infrastructure
Size of corridors and rooms	Nurse call system
Unit location	Alarm fire system
Nursing station location	Hand washing stations
Supply room location	Air conditioning unit
Finishes (walls, ceiling, floor)	Monitoring central station system
Medication room location	Elevator location
Staff room and lounges location	Sufficient number of telephones
Family waiting area location	An access card system
Isolation rooms location	Patient room reparation
Reception area	
Security area	
Cleaning utility area	
Solid utility area	
Equipment storage area	
Followed design standards	

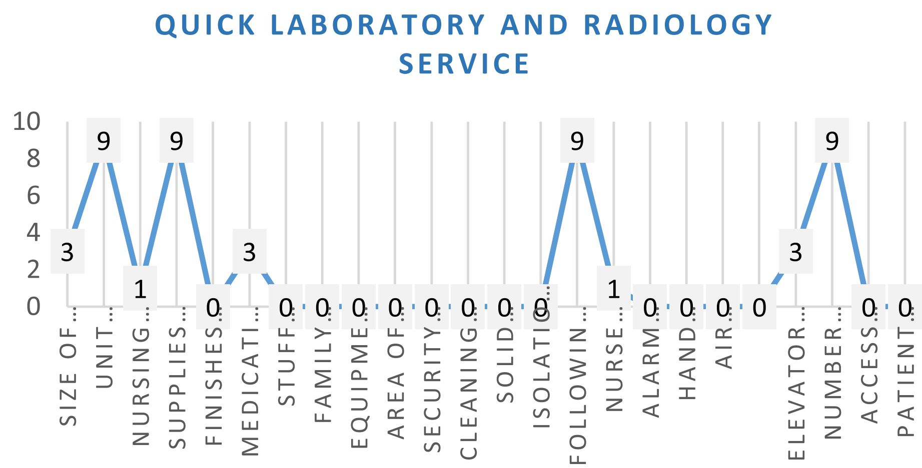

Fig. 1 An example of a customer requirement relationship with all technical requirements is presented on a scale 9, 3, and 1

assume we consider the customer requirement "quick laboratory and radiology services." The initial score was "4," the importance factor was "4," and the goal was "5." By substituting in Eq. (1), the improvement ratio is 1.25, and by substituting in Eq. (2), the relative weight is 5.

$$\mathrm{IR} = \mathrm{G} / \mathrm{S} \tag{1}$$

$$W_c = \mathrm{IR} \times \mathrm{IF} \tag{2}$$

Technical target sub-matrix

In this section, the weight of each technical requirement was calculated. The relationship sub-matrix and planning sub-matrix are used to determine the technical target sub-matrix. For each technical requirement, the resultant absolute weight (W_c) of each customer requirement was multiplied by the initial score (S). Then, the total summation of all customer requirements related to specific technical requirements was calculated to produce the absolute weight (W_t) as presented in Eq. (3). The normalized value of the absolute weight presents the relative weight [11, 15].

$$W_{ti} = \sum_{i=1}^{n} S_i \times W_{ci},\ i = 1, \ldots, n \tag{3}$$

where n is the number of technical requirements.

Calculation of gross factor

The gross square area is the entire area of enclosed space measured from the property's outer walls [16]. The aim of the study is to develop a method for calculating the GF to estimate the gross area of the ICU department. Therefore, the QFD model was built to determine which factors influence the GF based on customer requirements. The influential factors are put together into one equation depending on their resultant relative weights. The outcome of the equation is the proposed GF. The proposed equation is illustrated in Eq. (4), considering the influential factors, which are added to one to reflect the space required with respect to the original one.

$$Gross\ Factor = 1 + W_1 \times X_1 + W_2 \times X_2 + W_3 \times X_3 + \ldots\ldots + W_n \times X_n \tag{4}$$

where W is the relative weight of the technical requirements

X is the technical requirement

n is the number of technical requirements (influential factors)

Results

The QFD model has been applied in five steps to estimate the gross area of an ICU department depending on the calculated GF. The first and second steps were to identify the customer and technical requirements, respectively. A statistical analysis has been conducted for customer requirements to indicate the importance of these requirements. A sample of this analysis is introduced in Fig. 2, indicating only the items from 1 to 11. The third step was to demonstrate the relationships among the customer and technical requirements, as shown in Fig. 1. The fourth step was to determine the ranking of the customer requirements by calculating their relative weights. Lastly, the technical target weights were calculated based on their absolute and relative weights as discussed in the "Technical target sub-matrix" section.

The top five criteria of the QFD model were selected as influential criteria. Therefore, the GF is calculated as in (4) to obtain the new value. The results reveal the most important criteria are the following: following design standards (X_1), size of corridors and rooms (X_2), staff offices and lounges (X_3), standardized finishes (X_4), and nurse station area (X_5). According to the QFD model, the weights of the criteria are put in Eq. (5), as shown below. Taking all factors into account, some are quantitative, such as the size of corridors and rooms, while others are qualitative, such as standardized finishes. Two different hospitals are considered separately as a case study to validate our QFD model.

$$\text{Gross Factor } = 1 + 0.1952\text{X}_1 + 0.1273\text{X}_2 + 0.0769\text{X}_3 + 0.0741\text{X}_4 + 0.0669\text{X}_5$$

Case study 1

Case study 1 presents a public hospital with 220 beds. It is worth mentioning that getting the drawings of the hospital was challenging. Many attempts were made to obtain the layout design of the hospital. At the end, the hospital's drawings were obtained from the biomedical engineering department, which was not allowed to publish them. The layout of the hospital was used to determine the DNSA and the DGSA of the ICU to calculate the GF. The qualitative factors are substituted by "1" in cases of existence and "0" otherwise. The calculation of the corridor and room sizes is derived from the AUTOCAD program. As a result, the DNSA was calculated to be 524.8 m^2, and the DGSA was calculated to be 820.5 m^2. Thus, the GF is estimated to be 1.56. To determine the new GF, the factors are calculated as 1 for X_1, 0.239 for X_2, 0.055 for X_3, 1 for X_4, and 0.181 for X_5. Therefore, the new GF is calculated as in (4) to be 1.316, and the new gross area is 690.6 m^2. The difference between the old and new gross areas is 130 m^2. This means that

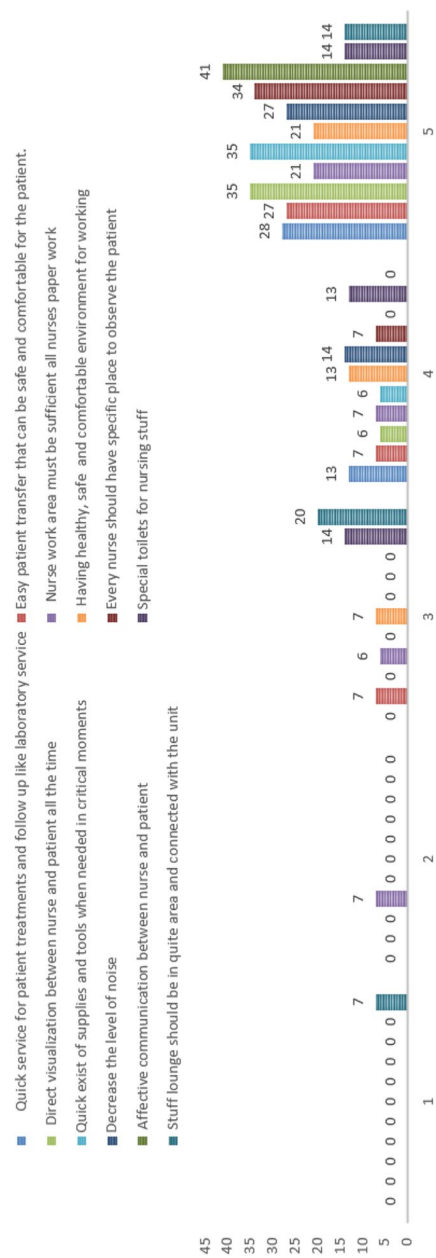

Fig. 2 Customer requirements response analysis including only 11 items of the conducted survey

Table 3 Budget difference between the old GF and the new GF for the first hospital

Factor	Price/unit (EGP)	Before	After
Walls paints	65	53332.5	44899.92
Floor (vinyl)	650	533325	448999.2
Ceiling blocks	130	106665	89799.84
Lightning (LED)	72.3	59322.15	49942.5264
Bed head units	15000	240,000	240,000
Scrub sink	3500	77,000	77,000
Total budget		1069644.65 EGB	950641.4864 EGB
Off (before–after)		**119003.1636 EGB (8000 $)**	

Table 4 Budget difference between the old GF and the new GF for the second hospital

Factor	Price/unit (EGP)	Before	After
Walls paints	65	44064.15	36831.86
Floor (vinyl)	650	440641.5	368318.6
Ceiling blocks	130	88128.3	73663.72
Lightning (LED)	72.3	49012.893	40968.3612
Bed head units	30,000	150,000	150,000
Scrub sink	5000	50,000	50,000
Total budget		821846.8 EGB	719782.5 EGB
Off (before–after)		**102064.3018 EGB (6800 $)**	

16% of the ICU area could be saved by applying the new GF. As a result, this could reflect on the budget in terms of finishing, lighting, and medical furniture. Another challenge we faced was estimating the costs. To tackle this issue, we looked for a contractor when setting costs. A contractor with 12 years of experience estimated the required items. Table 3 summarizes the items and the budgets before and after the implementation of the new GF. The results showed that around $8000 (mid-2022) was saved after applying the new GF.

Case study 2

Another public hospital with a capacity of 150 beds has been considered the second case study. As in the previous hospital, the AUTOCAD program was the source of the quantitative factors. As a result, the DNSA was calculated to be 435.9 m^2 and the DGSA was calculated to be 677.6 m^2. Thus, the GF is estimated to be 1.55. The factors are calculated as 1 for X_1, 0.228 for X_2, 0.054 for X_3, 1 for X_4, and 0.054 for X_5. Therefore, the new GF is calculated as in (4) to be 1.315. By multiplying the new GF by the net square area, the new gross area is 573.2 m^2. The difference between the old and new gross areas is 104.4 m^2. As in the previous hospital, 15.4% could be saved by the new GF. According to this new factor, the saved budget was determined as shown in Table 4. Obviously, the new GF saves around $6800 (mid-2022) in terms of lighting, finishing, and medical furniture. Considering the challenges of the previous case, except that the biomedical engineering department estimated the price list of finishings and furniture.

Discussion

The QFD methodology has been implemented to improve the design of an ICU department. Two cases have been studied to validate the model. The QFD has approved its ability to be utilized in hospital planning. The new GF value has been introduced in the final QFD equation. It is approximately 1.3 in both case studies, which is less than the implemented GF (1.5). As a result, having less GF affects not only the utilized spaces but also the customer's requirements. This reflects the environmental needs and business perspectives that can definitely grant customer satisfaction. Reducing the GF affects the estimated budget, which is essential to the business owners themselves. The amounts being saved in these two cases can be employed to extend the services provided to the patients.

The top five factors are related to hospital design, planning, and finishes. By comparing the two cases, it is found that the resulting GF is approximately the same, which is 1.3. This implies the GF should be a constant number, as was adopted before, which is 1.5. Although the difference between the old and new GF is not so great, it affects the utilized area and budget together. Taking this into account, saving space means new beds can be added in the ICU, but they are added from a new perspective by servicing the patients. Consequently, the costs of infrastructure, finishes, medical devices, and furniture could be saved for waste space.

Additional validation has been made by selecting the ICU of five private Egyptian hospitals. We adopted the same method to determine the GF by calculating the DNSA and DGSA from AUTOCAD drawings. Table 5 demonstrates the hospitals with the calculated parameters. As a result, the average GF was determined to be 1.49. As such, we recommend that the GF for any ICU department should not be less than 1.3, as indicated by our study.

It is worth mentioning that, according to our best knowledge, there is no prior method to estimate the GF in hospital design to be compared with our study. The study presented in [7] considered redesigning bed spacing in a complex environment without delving into the gross and net areas of the ICU. The ICU design has been qualitatively improved for bed spacing based on stakeholder involvement. Our study is unique in determining the GF in ICU departments.

Although this design demonstrates its efficiency in saving spaces and costs, we could not generalize the GF of 1.3 for ICU. More hospitals with various characteristics are needed for investigation. Another limitation of the proposed design is to consider the standard spaces among beds in the ICU. It is a crucial factor that should be considered for infection control and circulation.

Table 5 The calculated GF of random selected Egyptian hospitals

Hospital	Gross area (m^2)	Net area (m^2)	GF
H1	850.50	538.70	1.57
H2	677.61	435.88	1.55
H3	859.00	570.00	1.51
H4	250.00	175.00	1.42
H5	200.00	140.00	1.43

Conclusions

The quality function deployment has been used as a method for planning and improving area estimation in hospital design. Due to the importance of the ICU in the hospital, it has been selected for application. There are no clear guidelines in the literature for determining the gross factor for hospital departments. In practice, hospital planners calculate such a factor using a default value based on earlier, comparable projects. In order to address this issue, a planning model should be created. According to the best of our knowledge, this study presents a new method to calculate this factor using the QFD model. Two case studies have been applied to validate the model, which suggests that 15–16% of the ICU area could be saved. In an economic perspective, this area reduction can be translated into cost reduction and ICU bed addition. With the current worldwide pandemic situation, this is a pressing issue that needs to be taken into consideration. The money that is saved can also be applied to another hospital-related undertaking. Future work extends to many issues. More hospitals with different scales should be added for validation to see whether there is a difference in the gross factor or not. Moreover, different types of hospitals should be added for investigation, such as private and military hospitals. The proposed design could be investigated for standards compliance, such as the Facility Guidelines Institute (FGI) in terms of spaces, circulation, equipment, and safety. Besides, sustainability could be considered in design for some issues like ventilation and daylighting. The QFD method could be used as a general planning tool for hospital planning, and it could be customized for other departments.

Abbreviations

DGSF	Department gross square foot
DGSA	Department gross square area
DNSF	Department net square foot
DNSA	Department net square area
DoD	Department of Defense
ED	Emergency department
FGI	Facility guidelines institute
GF	Gross factor
GSA	Gross square area
HoQ	House of quality
ICU	Intensive care unit
IF	Importance factor
IR	Importance ratio
LFA	Logical framework approach
NSA	Net square area
QFD	Quality function deployment
US	United States
WHO	World Health Organization

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Authors' contributions
Both authors contributed to the conceptualization and methodology of the study. Both authors contributed to data analysis and interpretation. NS has contributed to the original manuscript's writing. MW has provided overall coordination and editing. Both authors read and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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