*sustainability*

MDPI

*Article*

# A Fuzzy Approach to Developing Scales for Performance Levels of Healthcare Construction Projects in Hong Kong

**Goodenough D. Oppong [1,*], Albert P. C. Chan [1], Man Wai Chan [1], Amos Darko [2], Michael A. Adabre [1] and Lekan D. Ojo [1]**

[1] Department of Building and Real Estate, Hong Kong Polytechnic University, 11 Yuk Choi Road, Hung Hom, Kowloon, Hong Kong; albert.chan@polyu.edu.hk (A.P.C.C.); wai.88.chan@polyu.edu.hk (M.W.C.); michael.a.adabre@connect.polyu.hk (M.A.A.); lekan-damilola.ojo@polyu.edu.hk (L.D.O.)

[2] Department of Construction Management, University of Washington, Seattle, WA 98195, USA; adarko@uw.edu

* Correspondence: goodenough.de.oppong@connect.polyu.hk

**Abstract:** The determinants of hospital project or healthcare project (HP) success are divergent and difficult to generalize because of the heterogeneous perceptions of various stakeholders. There is also a paucity of HP life cycle success evaluations from planning to post-construction phases. Meanwhile, the successful delivery and continual functionality of HPs are pivotal for sustainable development, as evident in the United Nations' Sustainable Development Goal 3 about ensuring healthy lives and promoting wellbeing for all people. To contribute to sustainable development, a novel evaluation framework is essential to define robust metrics of selected key performance indicators (KPIs) for monitoring and controlling HPs at the life cycle phases thereof. Fuzzy set theory, namely the bisector error method (BEM), was applied to questionnaire survey outputs of an expert panel to establish performance metrics of HPs within five grades, namely, poor, average, good, very good and excellent. The novel evaluation framework comprising indexes, indicators and grades are demonstrated on hypothetical HPs to provide objective, reliable and practical outcomes for performance comparison, benchmarking and improvement purposes. The findings show that a high standard is required for excellent planning, execution, and performance in HPs. The life cycle success evaluation framework is foundational in policymaking. Thus, policymakers can track the success of HPs by linking the performance metrics to goals and policy priorities in benchmarking and strategic planning for sustainable development in HPs.

**Keywords:** fuzzy set theory; healthcare projects; hospital projects; performance indexes; success evaluation; construction industry; Hong Kong

check for updates

Academic Editor: Maxim A. Dulebenets

Received: 21 November 2024
Revised: 21 January 2025
Accepted: 23 January 2025
Published: 31 January 2025

**Citation:** Oppong, G.D.; Chan, A.P.C.; Chan, M.W.; Darko, A.; Adabre, M.A.; Ojo, L.D. A Fuzzy Approach to Developing Scales for Performance Levels of Healthcare Construction Projects in Hong Kong. *Sustainability* **2025**, *17*, 1155. https://doi.org/10.3390/su17031155



## 1. Introduction

Sustainability has probably become the most discussed topic globally. This is evinced in the United Nations' Sustainable Development Goals 2030 (SDGs). Among the list of SDGs is encouraging good health and wellbeing (SDG 3). This goal is currently of special interest globally considering the recent COVID-19 pandemics, aging population, increasing population and underdeveloped healthcare facilities. To achieve good health and wellbeing while mitigating adverse environmental impacts, sustainable hospital or healthcare projects (HPs) are paramount. Regarding HPs in particular, sustainability is crucial because of the significant levels of waste generation, energy utilization, and life cycle costs. HPs comprise the planning, construction and operation of facilities and associated infrastructure for delivering all kinds of healthcare services. As at mid-2024, a total of USD 636.8 billion worth of HPs is being implemented worldwide in accordance with the "good health and wellbeing" agenda of the United Nations' SDGs 2030 about expanding good healthcare coverage to reach every global citizen [1]. Meanwhile, the deficit investment into and insufficient capacity of the worldwide healthcare system are presently undermined by actual healthcare needs [2]; basic healthcare services are accessible to only a minority of global citizens presently [3]; the current global population estimate of 8.2 billion will predictively increase by 3.7% in 2030, 18.3% in 2050 and 25.6% in 2085, and the elderly population ratio will increase from 9.1% in 2019 to 16.7% by 2050 [4]; and the COVID-19 pandemic exposed the weaknesses of sustainable healthcare provision worldwide. By implication, there is a need for global governments and organizations to continuously invest in HPs, which are the bedrock of healthcare systems, to ably match the healthcare needs of population demographics and dynamics. HPs are of inexhaustible special characteristics and features including meeting swiftly changing legislations, impeccable healthcare value delivery, complicated and dynamic implementation procedure, voluminous statutory approvals, marketplace pressures, high-level technological requirements, multiple contradicting requirements, etc. [5,6]. Owing to these performance-related factors, HPs are exceptionally challenging to plan, construct and operate.

For evaluating the success or performance areas of HPs, the key performance indicator (KPI) approach is the most utilized ahead of others such as balanced scorecard and post-occupancy evaluation [7–12]. Responsible practitioners define objectives for performance evaluation, select significant KPIs, gather and analyze relevant data, and present performance results to appropriate establishments or persons [13]. The use of KPIs for evaluating the performance of HPs in scholarly works is not without limitations. Basically, varying KPI frameworks have been recommended for evaluating different areas and perspectives of HPs [14,15], based on influencing factors such as the utilization purpose, target users, organizational nature and current industry trends [16]. Due to ever-changing performance expectations, there is a need for the several fragmentary KPI frameworks to be consolidated, updated and enhanced to be suitable for multitudes of HPs and organizations in the current industry. In addition, the literature on KPI frameworks is so much focused on the "what" performance areas to measure including cost, time, and quality [11,17]. However, there is limited scholarly progression on "how" these suggested performance areas could be methodically, objectively and reliably evaluated. In turn, individual organizations and practitioners are likely to rely on their subjective and inconsistent construction of meanings about these performance areas of HPs, thus inhibiting the usefulness of previously developed frameworks in practice. Additionally, KPI frameworks were developed to be suitable for isolated phases of HPs covering planning, construction, operation, etc. [18–20]. Meanwhile, these fragmented phases are practically interconnected and ensure the transmission and magnification of performance experiences from idea conception through construction to the operation of HPs. The multiplicative interactions between economic sustainability KPIs (e.g., cost performance and time performance) and social sustainability KPIs (e.g., quality performance and safety performance) at the construction phase could influence environmental sustainability KPIs (e.g., maintenance effectiveness), social sustainability KPIs (e.g., stakeholder/end-user satisfaction) and circular economy KPIs (e.g., functional capacity and utilization, and reliability and adaptability of facility) at the operation phase. In effect, KPIs should be perceived as interactive ingredients influencing value creation across the seamless life cycle phases of HPs.

The aim of the broader study is to develop a computer-assisted project success index system to measure, monitor, control, enhance and benchmark the performance of HPs. The current objectives are to (1) establish quantitative ranges (QRs) or performance grades of selected KPIs for differentiating life cycle success levels of HPs, and (2) demonstrate the comprehensive and objective evaluation system developed on HPs. In terms of theory, the study contributes to the research agenda on objective success evaluation and sustainability through the harmonization of experts' opinions about the pragmatic KPIs of the HP life cycle. The practical usefulness of the outcomes will advance the understanding of organizations and individuals on the "*whats*" and "*hows*" that define success so that HPs can be designed, constructed and operated successfully in Hong Kong.

*Healthcare System in Hong Kong*

Hong Kong has a population of 7.5 million people and is among the top five global jurisdictions with the highest population density [21]. Hong Kong together with Japan and the Republic of Korea have the topmost life expectancy at birth (i.e., $\geq$84 years) both at the group and world levels [4]. The jurisdiction's elderly population ratio will projectably exceed a quarter by 2036 and a third by 2054 [4,22]. The derived understanding is that there will be amplifying pressures to provide effective and efficient healthcare services to different population demographics. The Hong Kong government and several organizations have been perpetually investing in multiplying the collection of facilities and infrastructure upholding the healthcare system. Over the past few decades, the Health Bureau, Department of Health, Hospital Authority and Hong Kong Private Hospitals Association have been managing, developing and operationalizing the entire healthcare system. As of the first quarter of 2023, there are 43 hospitals and institutions, 49 specialist out-patient clinics and 74 general out-patient clinics (totaling over 30,000 beds) managed by the Hospital Authority and 14 major private healthcare facilities managed by the Hong Kong Private Hospitals Association [23].

Although the general standard of healthcare service delivery in both public and private sectors is highly commendable in Hong Kong, the public sector suffers from the extensive demand for surgical procedures within some clusters, and it can hardly cope with just a few [24]. To increase the public sector's capacity toward meeting healthcare needs, the Hong Kong government is presently implementing a continuous 20-year hospital development plan (2016 to 2036) of USD 64 billion total value for upgrading, expanding and developing multiple healthcare facilities [25]. Overall, the public sector's capacity will be increased by more than 15 thousand beds, over 90 new operating theatres, and other facilities [22,26]. The forecasted service supply from 2036 will help to reduce the unfavorable length of waiting times of patients in the public sector.

## 2. Healthcare Project Success

Construction literature is filled with several collections of performance criteria for predicting the success of diverse types of construction projects. The construction HP scope has risen to prominence around performance measurement because these projects are the mighty pillars underlying any working healthcare system globally. A thorough search of pertinent literature has revealed the proliferation of time, quality and cost performance as vital criteria for evaluating success in the planning and construction phases of HPs. These three criteria serve as the most basic and common system for evaluating the performance of construction projects historically. Their relevance is key in this study because HPs are of unique characteristics (e.g., complexity), for handling emergency healthcare situations, and for sustaining lives [5,8,11,19,20,27–31]. Accidents, injuries and casualties fraught the execution of construction HPs. Because the rights and values of human resources are to be protected, several safety mechanisms and systems are implemented by regulation or responsibility to curb the spate of safety issues on HP sites. Thus, safety performance is hugely acknowledged to be an important criterion for determining the success of HP execution [5,31–34]. In addition, the planning and construction of HPs is taking a more scientific approach to achieving better outcomes through the innovation of inputs (e.g., processes, techniques, resources, technologies, etc.). Measurable improvement is guaranteed when construction organizations implement original or adopted innovative ideas in HPs, and thus serve as a good yardstick for evaluating success [5,33–35].

In the post-construction phase, the fulfillment of the stakeholders and users of HP outputs can provide a precise judgment on the truthfulness of success. Although this criterion may be subjective in nature, scholars consider it very useful in capturing the social context of HP success evaluation [14,17,33,36]. Additionally, the actual functionality encapsulates the defined scope, objectives, and requirements upon which the HP is implemented. Assessment of the functionality of HPs in terms of suitability for purpose, value, capacity and utilization is a great step toward realizing its success [7,15,18,34,36–38]. Again, the quality and frequency of maintenance activities carried out to restore HP outputs to commendable conditions can be useful in measuring operational success. Expectedly, proper maintenance of HP outputs will lead to better conditions of facilities and delivery of service, and vice versa. A plethora of theoretical evidence supports the use of maintenance practice as a success measure of HPs [7,18,39–43]. Moreover, HP outputs may change their usage function over time out of necessity. For instance, during an outbreak of disease, more HP spaces will be devoted to tackling the impacts, usually differing from their primary usage purpose. Hence, the flexibility of HP outputs to be adapted for new functional purposes is an aspect of the success definition [35,36]. The ten (10) selected criteria or KPIs for measuring HP success in the construction industry are summarized in Table 1, with appropriate definitions.

**Table 1.** KPIs of running healthcare projects.

| No. | KPIs | Definitions | References |
|---|---|---|---|
| 1 | Construction cost performance | Total cost of project, e.g., within or exceeding budget | Chan et al. [27]; Chan et al. [28]; Al-Tmeemy et al. [29]; Chan [30]; Zuo et al. [31]; Iskandar et al. [20]; Ling and Li [9]; Rosacker et al. [8]; Sharma et al. [5]; Wai et al. [19]; Gokhale and Gormley [32]; Do et al. [33]; Choi et al. [34]; Choi et al. [38]; Buelow et al. [17]; Ahmad et al. [14] |
| 2 | Construction time performance | Overall time of project, e.g., within or behind schedule | Chan et al. [27]; Chan et al. [28]; Al-Tmeemy et al. [29]; Chan [30]; Zuo et al. [31]; Iskandar et al. [20]; Ling and Li [9]; Rosacker et al. [8]; Sharma et al. [5]; Wai et al. [19]; Gokhale and Gormley [32]; Do et al. [33]; Choi et al. [34]; Choi et al. [38]; Buelow et al. [17] |
| 3 | Construction quality performance | Level of quality of project, e.g., high, moderate, or low quality | Chan et al. [27]; Chan et al. [28]; Al-Tmeemy et al. [29]; Chan [30]; Zuo et al. [31]; Iskandar et al. [20]; Ling and Li [9]; Sharma et al. [5]; Wai et al. [19]; Gokhale and Gormley [32]; Do et al. [33]; Adamy and Abu Bakar [15]; Adamy and Abu Bakar [10]; Adamy [12] |
| 4 | Construction safety performance | Rate and magnitude of accidents in project, e.g., low, medium or high rate | Chan et al. [27]; Chan et al. [28]; Al-Tmeemy et al. [29]; Chan [30]; Zuo et al. [31]; Sharma et al. [5]; Gokhale and Gormley [32]; Do et al. [33]; Choi et al. [34] |
| 5 | Innovation and improvement | Number of new initiatives introduced for improvement, e.g., modern technologies and advanced techniques | Sharma et al. [5]; Talib et al. [35]; Do et al. [33]; Choi et al. [34] |

**Table 1.** *Cont.*

| No. | KPIs | Definitions | References |
|---|---|---|---|
| 6 | Functional suitability | Extent of fitness of facility for purpose, e.g., less, more or perfectly fit for purpose | Chan et al. [27]; Chan et al. [28]; Al-Tmeemy et al. [29]; Chan [30]; Zuo et al. [31]; Lai and Yuen [40]; Lai et al. [39]; Lavy et al. [7]; Rosacker et al. [8]; Sharma et al. [5]; Shohet [37]; Talib et al. [35]; Lai and Yuen [18]; Gokhale and Gormley [32]; Edum-Fotwe et al. [36]; Choi et al. [34]; Choi et al. [38]; Buelow et al. [17]; Ahmad et al. [14]; Adamy and Abu Bakar [15]; Adamy and Abu Bakar [10]; Adamy [12] |
| 7 | Maintenance effectiveness and efficiency | Frequency or quality of maintenance activities, e.g., zero, less or more maintenance backlog | Lai and Yuen [18]; Lai et al. [39]; Lai et al. [40]; Lavy et al. [7]; Li et al. [41]; Omar et al. [42]; Omar et al. [43]; Shohet [37]; Talib et al. [35]; Marzouk and Hanafy [44]; Lai and Yuen [45]; Gokhale and Gormley [32]; Edum-Fotwe et al. [36] |
| 8 | Stakeholder/end-user satisfaction | Level of satisfaction of stakeholders/end-users with project outcomes | Chan et al. [28]; Al-Tmeemy et al. [29]; Chan [30]; Lai and Yuen [40]; Lavy et al. [7]; Li et al. [41]; Rosacker et al. [8]; Talib et al. [35]; Wai et al. [19]; Lai and Yuen [45]; Edum-Fotwe et al. [36]; Do et al. [33]; Buelow et al. [17]; Ahmad et al. [14]; Adamy and Abu Bakar [19] |
| 9 | Functional capacity and utilization | Level of efficiency of space utilization in facility, e.g., under-used or over-used space | Lai and Yuen [18]; Lavy et al. [7]; Shohet [37]; Talib et al. [35]; Edum-Fotwe et al. [36]; Choi et al. [34]; Choi et al. [38]; Adamy and Abu Bakar [15] |
| 10 | Flexibility and adaptability of facility | Extent of reliability and flexibility of facility to adapt to newer/modern use or purpose over time | Talib et al. [35]; Edum-Fotwe et al. [36] |

## 3. Research Methods

Due to the nature of the study, a quantitative methodology comprising a questionnaire survey and fuzzy set theory was utilized to achieve the objectives. The questionnaire survey was issued to solicit the opinions of experts regarding the performance expectations for different performance grades of the KPIs and quantitative indicators (QIs) of HP success. In addition, the fuzzy set theory was engaged to define appropriate ranges for the different performance grades. The research framework designed for the study is illustrated in Figure 1.

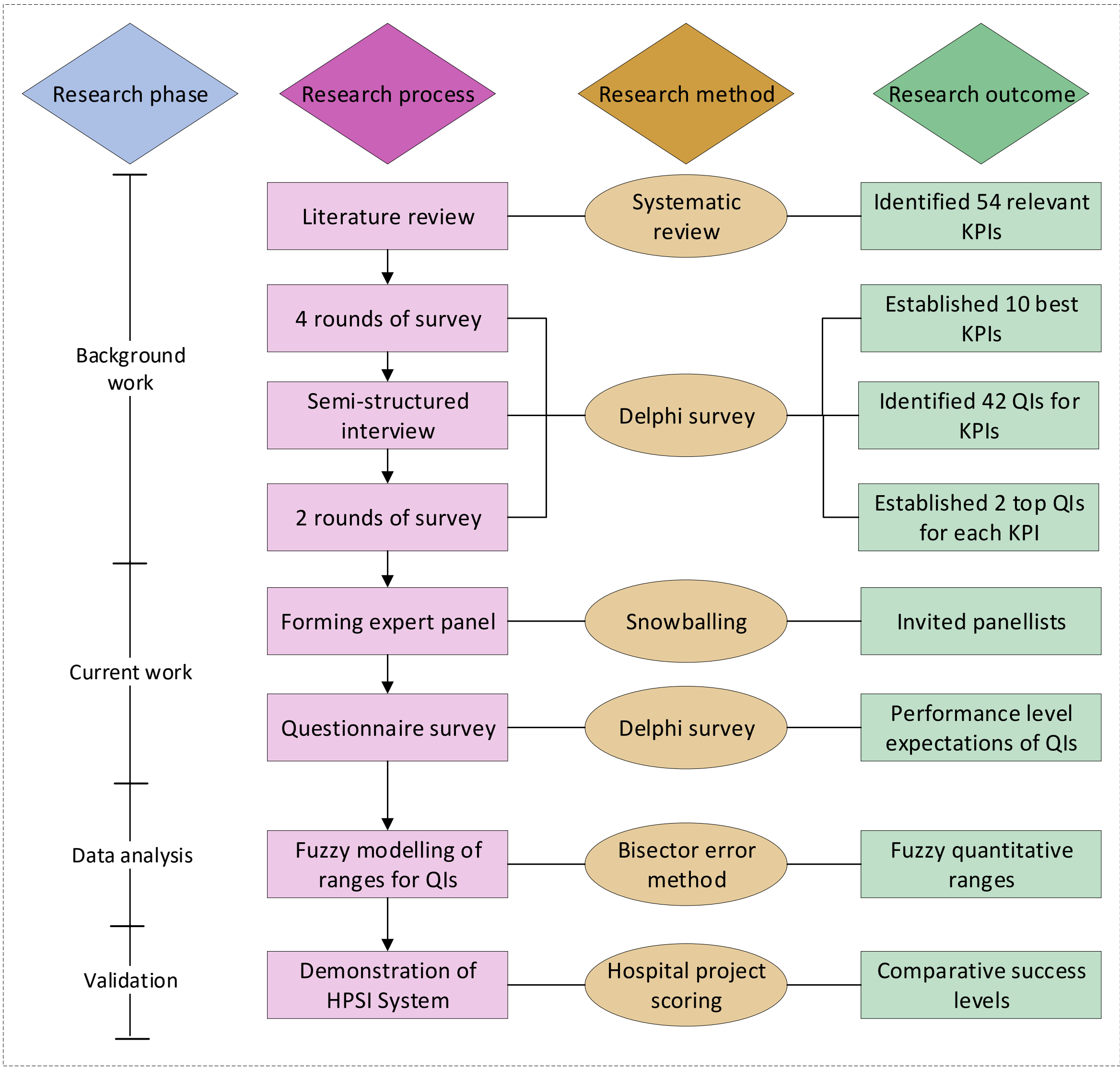



**Figure 1.** Overview of research framework.

### 3.1. Background Research Work

A number of research activities were conducted to constitute the foundation of the present study. First, a systematic literature review was performed on performance measurement of HPs to identify 54 relevant KPIs. One set of 27 KPIs is suitable for the planning and construction phases and the other set of 27 KPIs is applicable for the post-construction phase of HPs. Second, a 4-round Delphi questionnaire survey was conducted for experts to identify and rate the most significant KPIs for evaluating the success of HPs. The sample sizes of expert responses in these four rounds are 19, 19, 15 and 15, respectively. Eventually, two indexes comprising 5 shortlisted weighted KPIs separately were developed for the planning and construction phases and the post-construction phase of the HPs. Each index is a linear and additive weighting model that is evaluated by the summation of the weighted KPIs. Third, a list of 42 QIs for representing the 10 shortlisted KPIs was formalized through semi-structured interviews with Delphi experts. Finally, the experts were requested to rate the appropriateness levels of the QIs through 2 rounds of the Delphi questionnaire survey. Subsequently, the two most appropriate QIs were established to define each KPI. While 5 experts contributed experiential knowledge during the interviews, 16 experts participated in both Delphi survey rounds. The summary of the background work underlying this study is captured in Figure 2.

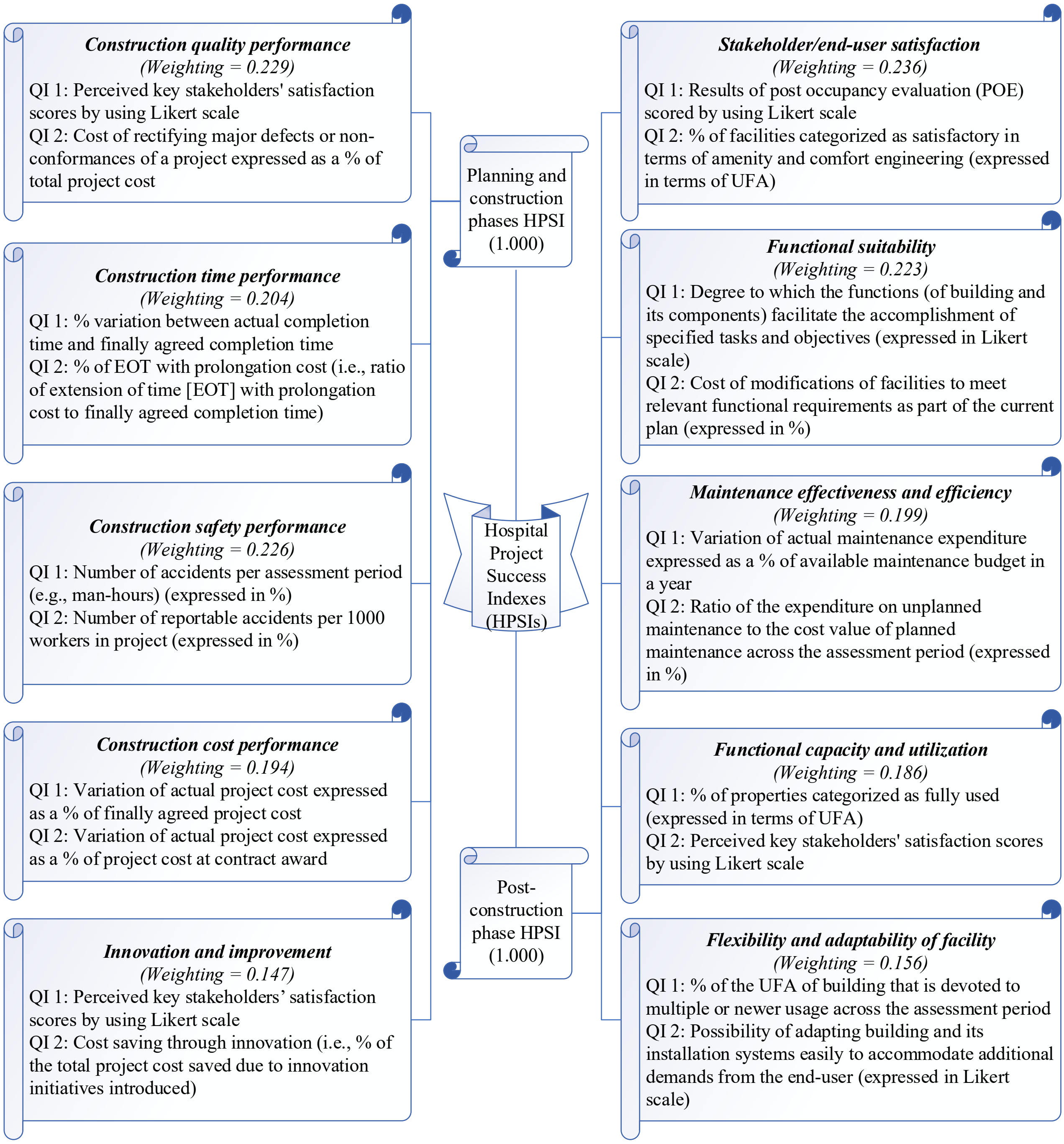



**Figure 2.** Summary of background work underlying this study. Note: part of the background work is already presented in Oppong et al. (2025) [46].

### 3.2. Data Collection

Due to the lack of historical data on the performance grades of the KPIs of HPs, the Delphi method is relevant for fetching specific details from the long-term experiences of experts. Delphi method permits experts to resolve sophisticated problems with collective opinions; self-approves results with the iteration of rounds; controls response biases and conformation pressures; prevents direct engagements among experts; enhances truthfulness and confidentiality; ensures valid balanced responses through panel diversity; and underlies objective analysis of data [47–49]. It is similarly utilized in construction engineering and management topics such as team integration [50], procurement selection [51] and success measurement [52,53].

Through purposive sampling, the respondents were drawn from the Hospital Authority, Architectural Services Department and construction firms that are engaged in HP development in Hong Kong. The initially identified respondents helped to nominate other qualified respondents within their workplaces or networks through snowballing sampling. It is important to note that the target respondents already participated in prior rounds of the Delphi survey. In addition to their organizational roles, the 16 identified respondents matched the following eligibility parameters to become panel experts [51,53,54]:

1. Knowledge and in-depth understanding of the planning, construction and/or operation of HPs;
2. Recent hands-on experience in planning, constructing and/or operating HPs; and
3. Play leading roles in the construction industry.

Considering their job burden and availability, only 13 experts responded to the questionnaire survey, representing an 81% response rate. These figures are adequate and comparable to other similar studies including Yeung et al. [55] and Ibrahim et al. [56]: they received 12 and 17 responses out of panel sizes of 17 and 17, respectively. In addition, this study's sample is beyond the general benchmark of 8 to 12 experts' requirements for effectively solving problems through the Delphi technique [47]. The diversity of professional backgrounds, client sectors, lifecycle phases, experience levels and project numbers reveals a balanced pool of expert judgments to model HP success across the lifecycle (Table 2).

**Table 2.** Demographic information of the panel experts.

| Demographic Characteristics | No. | % | Demographic Characteristics | No. | % |
|---|---|---|---|---|---|
| Professional background | | | Level of experience | | |
| Project/construction manager | 4 | 30.77% | 1–5 years | 7 | 53.85% |
| Quantity surveyor | 3 | 23.08% | 6–10 years | 2 | 15.38% |
| Architect | 1 | 7.69% | 11–15 years | 1 | 7.69% |
| Facility/property manager | 1 | 7.69% | ≥15 years | 3 | 23.08% |
| Engineer | 2 | 15.38% | Total | 13 | 100% |
| Hospital administrator | 1 | 7.69% | | | |
| Medical professional | 1 | 7.69% | Number of healthcare projects | | |
| Total | 13 | 100% | 1–2 | 6 | 46.15% |
| | | | 3–4 | 2 | 15.38% |
| Sector of client | | | 5–6 | 1 | 7.69% |
| Public | 11 | 84.62% | ≥6 | 4 | 30.77% |
| Private | 3 | 23.08% | Total | 13 | 100% |
| Quasi-public | 1 | 7.69% | | | |
| Phase of healthcare project | | | | | |
| Planning phase | 7 | 53.85% | | | |
| Construction phase | 12 | 92.31% | | | |
| Post-construction phase | 6 | 46.15% | | | |

### *3.3. Fuzzy Set Theory (FST)*

Upon data collection, FST was utilized to calibrate different QRs (i.e., boundaries) for the QIs of the KPIs of HP success. FST is a dimension of contemporary mathematics that was invented by Zadeh [57] for handling the vagueness naturally resident in the intellectual and reasoning processes of man. It has developed into a potent mathematical tool for modeling several vague and complicated phenomena arising from partial, uncertain and imperfect data characterizing practical world systems. The uniqueness of FST from classical set theory, as well as the reason for fuzziness, is that membership of the set elements follows a gradual rather than sudden transition from zero-membership to full-membership [58]. In the construction industry, the membership functions and linguistic variables are probably the most applied FST concepts to decision systems in addressing vagueness and uncertainty [55]. Linguistic variables such as "very good" performance or "excellent" performance have no clear-cut definition [59].

The FST technique called the modified horizontal approach [60,61], which combines the horizontal approach and graphical approach, is utilized in the study. Because of its inherent limitations, the modified horizontal approach was enhanced with the amalgamation of the bisector error method (BEM) for constructing fuzzy membership functions [55,62]. In using the constrained best-fit lines to construct membership functions, the BEM takes the midpoints of the horizontal and vertical distances, thus minimizing the residual sum of squares. The BEM is based on the horizontal error method (HEM) and vertical error method (VEM). Practically, this newer method provides results with minimum deviations from the two asymmetric $X$ and $Y$ regression lines [63]. Because of its precision and simplicity, the modified horizontal approach with the BEM is utilized for diverse construction topics such as alliance team integration performance [56], relationship-based project performance [55], partnering project performance [62] and design-build operational variations selection [64]. The fuzzy QRs, representing the performance grades of the KPIs, were established by considering the intersection points of the successive constrained best-fit lines of the fuzzy membership functions.

### *3.4. Mean and Standard Deviation Values of the Performance Grades of KPIs*

In the questionnaire, the experts were requested to score their expected values for the five performance grades of poor, average, good, very good and excellent against selected percentile scales and 10-point Likert scales. Due to the expertise of the panelists, it is deemed that they understood the formulae and scales by which they gave appropriate judgments on the performance grades. The mathematical formulas for computing appropriate values of the QIs of KPIs are attached as Appendix A. Table 3 presents the mean and standard deviation values of the five performance grades of the QIs. A general observation shows that there exist some differences in the opinions of experts. In terms of the percentile scales, the most dispersed expert opinions concern the QIs of construction safety performance, which are "number of reportable accidents per 1000 workers in project (expressed in %)" (SD = 15.43; excellent performance) and "number of accidents per assessment period (e.g., man-hours) (expressed in %)" (SD = 14.93; excellent performance). For the Likert scales, the utmost distributed expert judgments on the performance grades are about the "degree to which the functions (of building and its components) facilitate the accomplishment of specified tasks and objectives (expressed in Likert scale)" (SD = 1.34; poor performance) of functional suitability and "perceived key stakeholders' satisfaction scores by using Likert scale" (SD = 1.25; very good performance) of innovation and improvement.

**Table 3.** The mean and standard deviation values of the five performance levels of KPIs.

| | Quantitative Indicators (QIs) of Selected Key Performance Indicators (KPIs) | Successive Performance Grades | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Poor | | Average | | Good | | Very Good | | Excellent | |
| | | M | SD | M | SD | M | SD | M | SD | M | SD |
| | *KPI 1: Construction quality performance* | | | | | | | | | | |
| QI 1 | Perceived key stakeholders' satisfaction scores with construction quality by using Likert scale. | 2.00 | 0.91 | 4.46 | 1.05 | 6.15 | 1.07 | 7.88 | 1.16 | 9.38 | 0.85 |
| QI 2 | Cost of rectifying major defects or non-conformances of a project expressed as a percentage of total project cost. | 8.12% | 2.21 | 5.77% | 1.83 | 4.19% | 1.60 | 2.50% | 1.29 | 0.54% | 0.48 |
| | *KPI 2: Construction time performance* | | | | | | | | | | |
| QI 1 | Percentage variation between actual completion time and finally agreed completion time | 18.00% | 6.04 | 5.38% | 4.44 | −0.69% | 3.61 | −6.08% | 4.11 | −13.00% | 6.94 |
| QI 2 | Percentage of EOT with prolongation cost (i.e., ratio of extension of time [EOT] with prolongation cost to finally agreed completion time). | 16.92% | 4.13 | 10.15% | 2.76 | 5.77% | 2.28 | 3.27% | 1.67 | 0.73% | 1.24 |
| | *KPI 3: Construction safety performance* | | | | | | | | | | |
| QI 1 | Number of accidents per assessment period (e.g., man-hours) (expressed in %) | 120.77% | 10.96 | 103.46% | 8.26 | 88.85% | 9.61 | 78.46% | 10.28 | 65.38% | 14.93 |
| QI 2 | Number of reportable accidents per 1000 workers in project (expressed in %), i.e., accidents resulting in an injury with incapacity for more than three days | 120.38% | 11.08 | 103.08% | 7.78 | 89.23% | 9.54 | 78.46% | 10.28 | 66.15% | 15.43 |
| | *KPI 4: Construction cost performance* | | | | | | | | | | |
| QI 1 | Variation in actual project cost expressed as a percentage of finally agreed project cost. | 15.54% | 7.08 | 4.15% | 5.71 | −2.31% | 3.88 | −9.15% | 5.01 | −16.00% | 6.68 |
| QI 2 | Variation in actual project cost expressed as a percentage of project cost at contract award. | 17.62% | 5.90 | 5.27% | 4.88 | −2.31% | 3.30 | −10.04% | 3.71 | −18.38% | 5.45 |
| | *KPI 5: Innovation and improvement* | | | | | | | | | | |
| QI 1 | Perceived key stakeholders' satisfaction scores by using Likert scale. | 1.92 | 0.86 | 4.38 | 1.12 | 6.23 | 1.24 | 7.69 | 1.25 | 9.12 | 1.12 |
| QI 2 | Cost saving through innovation (i.e., percentage of the total project cost saved due to innovation initiatives introduced) | 0.69% | 0.75 | 2.69% | 1.25 | 4.77% | 1.48 | 6.62% | 1.76 | 8.65% | 2.15 |
| | *KPI 6: Stakeholder/end-user satisfaction* | | | | | | | | | | |
| QI 1 | Results of post occupancy evaluation (POE) scored by using Likert scale. | 2.23 | 1.17 | 4.46 | 0.97 | 6.15 | 0.90 | 7.81 | 0.80 | 9.35 | 0.75 |

**Table 3.** *Cont.*

| | **Quantitative Indicators (QIs) of Selected Key Performance Indicators (KPIs)** | **Successive Performance Grades** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Poor** | | **Average** | | **Good** | | **Very Good** | | **Excellent** | |
| | | **M** | **SD** | **M** | **SD** | **M** | **SD** | **M** | **SD** | **M** | **SD** |
| QI 2 | Percentage of facilities categorized as satisfactory in terms of amenity and comfort engineering (expressed in terms of usable floor area [UFA]). | 50.38% | 11.08 | 61.69% | 8.45 | 73.46% | 6.25 | 84.62% | 5.19 | 95.54% | 5.21 |
| | *KPI 7: Functional suitability* | | | | | | | | | | |
| QI 1 | Degree to which the functions (of building and its components) facilitate the accomplishment of specified tasks and objectives (expressed in Likert scale). | 2.15 | 1.34 | 4.50 | 0.96 | 6.27 | 0.83 | 7.85 | 0.55 | 9.37 | 0.64 |
| QI 2 | Cost of modifications of facilities to meet relevant functional requirements as part of the current plan (expressed in %). | 4.38% | 0.82 | 3.00% | 0.58 | 1.98% | 0.60 | 0.96% | 0.32 | 0.19% | 0.25 |
| | *KPI 8: Maintenance effectiveness and efficiency* | | | | | | | | | | |
| QI 1 | Variation in actual maintenance expenditure expressed as a percentage of available maintenance budget in a year. | 31.15% | 14.46 | 11.15% | 10.24 | −4.62% | 6.60 | −17.54% | 8.97 | −31.92% | 13.77 |
| QI 2 | Ratio of the expenditure on unplanned maintenance to the cost value of planned maintenance across the assessment period (expressed in %). | 37.69% | 13.79 | 24.31% | 9.69 | 17.23% | 8.36 | 8.85% | 4.86 | 3.08% | 3.09 |
| | *KPI 9: Functional capacity and utilization* | | | | | | | | | | |
| QI 1 | Percentage of properties categorized as fully used (expressed in terms of usable floor area [UFA]). | 56.92% | 10.71 | 71.54% | 8.01 | 80.00% | 5.40 | 87.69% | 4.84 | 96.54% | 3.76 |
| QI 2 | Perceived key stakeholders' satisfaction scores by using Likert scale | 2.23 | 0.93 | 4.42 | 1.00 | 6.38 | 1.04 | 7.88 | 1.00 | 9.27 | 0.83 |
| | *KPI 10: Flexibility and adaptability of facility* | | | | | | | | | | |
| QI 1 | Percentage of the usable floor area (UFA) of building that is devoted to multiple or newer usage across the assessment period. | 6.15% | 6.18 | 16.15% | 5.46 | 24.62% | 6.60 | 32.31% | 7.80 | 40.38% | 9.46 |
| QI 2 | Possibility of adapting building and its installation systems easily to accommodate additional demands from the end-user (expressed in Likert scale). | 1.92 | 1.19 | 4.15 | 1.14 | 6.19 | 1.07 | 7.58 | 0.86 | 9.15 | 0.69 |

Note: QI 1 and QI 2 are the top quantitative indicators established for each selected KPI.

The deviations in the expectations of experts are apparent and can even create confusion in practice. For instance, the experts assigned as low as 10% and as high as 35% for good performance of "percentage of the usable floor area (UFA) of building that is devoted to multiple or newer usage across the assessment period" (flexibility and adaptability of facility). These scores somewhat overlap with the experts' expectations for very good performance of the same QI (i.e., 15% to 40%). This means that a practitioner can easily consider good performance to be 12% and another will regard good performance to be 34%, creating wide performance interpretation gaps in the industry. In the worst case, some practitioners could interpret 20% of the same QI as very good performance and other practitioners may regard 30% as rather good performance, destroying the logic of successive performance grades. Though the mean scores of the QI (i.e., 6.15%, 16.15%, 24.62%, 32.31% and 40.38%) can be useful as a quick rule of thumb for differentiating successive performance grades of HPs, defining appropriate QRs to incorporate the performance expectations of assessors is logical. Responding to these realistic problems with such a comprehensive and systematic tool will assist assessors with great flexibility to generally, practically and reliably evaluate HP success. FST was chosen ahead of other approaches (e.g., mean value analysis, fuzzy gap analysis, baseline and target analysis, etc.) to define QRs because of its practicality and usefulness.

### *3.5. Constructing Fuzzy Membership Functions with Bisector Error Method*

In analyzing the experts' opinions using the modified horizontal approach with BEM, the steps followed are namely [56,62,64]: (1) quantifying fuzzy QIs; (2) identifying the $X$ values of the membership functions; (3) identifying the $A$ values of the membership functions; and (4) formulating the fuzzy membership functions with the BEM.

Step 1: Quantifying fuzzy quantitative indicators

The panel experts provided numerical values in percentages and Likert scores $(V_i)$ against the five performance grades of the QIs, i.e., poor, average, good, very good and excellent. The percentage values $(V_{1-13})$ provided by experts for the QI 2 of construction quality performance in terms of poor performance is captured in Table 4.

Step 2: Identifying $X$ values of membership functions

**Table 4.** Quantification of QI 2 of construction quality performance (poor performance).

| Experts | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Poor performance expectation (%) | 3 | 5 | 6 | 8 | 8 | 8 | 9 | 9 | 9.6 | 10 | 10 | 10 | 10 |

The $X_i$ values of the fuzzy membership function are the elements of the universe of discourse defining the fuzzy set [55,64]. The $X_i$ values are taken as the averages of $(V_i)$ values captured within the bands $B_i$ $(i = 1, 2, 3, \ldots, k)$ assigned by panel experts. The $X_i$ values are established from the range of the $V_i$ values for respective QIs and the corresponding number of bands $k$. In determining the number of bands $k$, the Bharathi-Devi and Sarma [65] formula is engaged (Equation (1)):

$$k = 1.87(N-1)^{\frac{2}{5}} \tag{1}$$

where $N$ is the sample size of experts responding to respective QI.

Given that 13 experts provided the performance grade expectation scores for all QIs, the number of bands $k$ is computed as follows:

$$k = 1.87(13-1)^{\frac{2}{5}} = 5.05$$

By approximating the value, 5 bands are utilized for categorizing the scores $(V_i)$ of experts. Considering Table 4, the lowest and highest $V_i$ values of the QI 2 of construction quality performance (poor performance) are 3% and 10%. Accordingly, this range (10% − 3% = 7%) is divided into 5 equal bands of width 1.4%, and used to categorize the $V_i$ values. The $X_i$ values are derived by computing the averages of all $V_i$ values falling within respective bands. For instance, the $X_i$ value for Band 4 is 8% (Table 5).

Step 3: Identifying $A$ values of membership functions

**Table 5.** Computation of $X$ and $A$ values for poor performance of QI 2 of construction quality performance.

| Band | Range (%) | Number of Values Within Each Band | Computation for Each Value of $X_i$ (%) | Computation for Each Value of $A_i$ | Std ($A_i$) |
|---|---|---|---|---|---|
| 1 | 3.0–4.4 | 1 | 3%/1 = 3% | 1/7 = 0.143 | 0.0068 |
| 2 | 4.4–5.8 | 1 | 5%/1 = 5% | 1/7 = 0.143 | 0.0068 |
| 3 | 5.8–7.2 | 1 | 6%/1 = 6% | 1/7 = 0.143 | 0.0068 |
| 4 | 7.2–8.6 | 3 | (8% × 3)/3 = 8% | 3/7 = 0.429 | 0.0114 |
| 5 | 8.6–10 | 7 | [(10% × 4) + (9% × 2) + 9.6%]/7 = 9.66% | 7/7 = 1.000 | 0.0000 |

The $A_i$ values denote the levels of membership of the elements of the fuzzy set. The $A_i$ values are determined by Equation (2) as follows [60]:

$$A_i = n(B_i)/n_{max} \quad \text{for } i = 1,\ 2,\ 3, \ldots k \tag{2}$$

where $n(B_i)$ stands for the number of $V_i$ values falling within a specific band $B_i$ and $n_{max}$ corresponds to the greatest value among all the $n(B_i)$ with $i = 1,\ 2,\ 3, \ldots k$. From Table 5, Band 4 with a range of 7.2–8.6% entails 3 $V_i$ values and the greatest value of $n(B_i)$ is 7. Therefore, the $A_4$ value is calculated as 3 over 7 to obtain 0.429. Again, the corresponding standard deviation $std(A_i)$ values were computed to verify if the estimated memberships were acceptable (Equation (3)). It is reasonable to accept the estimation of memberships where the $std(A_i)$ values are lower than the respective $A_i$ values [60]. All the computed $std(A_i)$ values were found to be below the respective $A_i$ values, and therefore, the estimated memberships are valid for further analysis.

$$std(A_i) = A_i \times \left(1 - A_i^{1/2}\right)/N \tag{3}$$

Step 4: Formulating fuzzy membership functions

A sample of the resultant fuzzy membership functions from the study is presented in Table 6. Based on the pairing of the $X$ and $A$ values of each performance grade of QIs, scatter diagrams expressing the fuzzy membership functions were plotted. By following the BEM, the best-fit lines were constructed to connect the discrete points of the fuzzy membership functions using MATLAB R2016a. The degree of membership of elements belonging to fuzzy sets ranges from 0 to 1, with 0 indicating non-membership and 1 showing full membership [55]. Commonly, fuzzy membership functions are triangular or trapezoidal in shape, and it is reasonable to constrain the best-fit lines to pass through the vertexes with full membership [61]. Upon constructing the best-fit lines of the five performance grades of respective QIs on the same graphs, the intersection points of successive best-fit lines reveal the same levels of membership. Logically, these intersection points serve as boundaries, helping to define fuzzy QRs for successive performance grades of the QIs. The fuzzy QRs for all QIs of the 10 selected KPIs are summarized in Tables 6 and 7.

**Table 6.** *X* and *A* values for poor performance of QI 2 of construction quality performance.

| Percentage (*X*) | Degree of Membership (*A*) |
|---|---|
| 3% | 0.143 |
| 5% | 0.143 |
| 6% | 0.143 |
| 8% | 0.429 |
| 9.66% | 1.000 |

**Table 7.** Fuzzy QRs of the KPIs at the planning and construction phases of healthcare projects.

| | Successive Performance Levels | | | | |
|---|---|---|---|---|---|
| | Poor | Average | Good | Very Good | Excellent |
| Construction quality performance (QI 1) | <4.25 | ≥4.25 to <5.34 | ≥5.34 to <6.77 | ≥6.77 to <8.90 | ≥8.90 |
| | <2.92 | ≥2.92 to <5.35 | ≥5.35 to <6.79 | ≥6.79 to <8.90 | ≥8.90 |
| | <3.42 | ≥3.42 to <5.34 | ≥5.34 to <6.78 | ≥6.78 to <8.90 | ≥8.90 |
| Construction quality performance (QI 2) | >7.23% | ≤7.23% to >4.63% | ≤4.64% to >3.42% | ≤3.42% to >1.00% | ≤1.00% |
| | >7.32% | ≤7.32% to >4.63% | ≤4.63% to >3.42% | ≤3.42% to >1.00% | ≤1.00% |
| | >7.28% | ≤7.28% to >4.63% | ≤4.63% to >3.42% | ≤3.42% to >1.00% | ≤1.00% |
| Construction time performance (QI 1) | >10.00% | ≤10.00% to >2.62% | ≤2.62% to >−3.03% | ≤−3.03% to >−7.73% | ≤−7.73% |
| | >10.00% | ≤10.00% to >2.82% | ≤2.82% to >−2.71% | ≤−2.71% to >−7.74% | ≤−7.74% |
| | >10.00% | ≤10.00% to >2.72% | ≤2.72% to >−2.86% | ≤−2.86% to >−7.74% | ≤−7.74% |
| Construction time performance (QI 2) | >11.89% | ≤11.89% to >7.17% | ≤7.17% to >4.07% | ≤4.07% to >1.29% | ≤1.29% |
| | >11.33% | ≤11.33% to >7.14% | ≤7.14% to >3.88% | ≤3.88% to >1.17% | ≤1.17% |
| | >11.57% | ≤11.57% to >7.16% | ≤7.16% to >3.96% | ≤3.96% to >1.23% | ≤1.23% |
| Construction safety performance (QI 1) | >102.56% | ≤102.56% to >98.00% | ≤98.00% to >88.00% | ≤88.00% to >78.07% | ≤78.07% |
| | >102.47% | ≤102.47% to >98.00% | ≤98.00% to >88.00% | ≤88.00% to >78.46% | ≤78.46% |
| | >102.51% | ≤102.51% to >98.00% | ≤98.00% to >88.00% | ≤88.00% to >78.27% | ≤78.27% |
| Construction safety performance (QI 2) | >102.72% | ≤102.72% to >98.00% | ≤98.00% to >88.00% | ≤88.00% to >79.47% | ≤79.47% |
| | >102.66% | ≤102.66% to >98.00% | ≤98.00% to >88.00% | ≤88.00% to >79.88% | ≤79.88% |
| | >102.69% | ≤102.69% to >98.00% | ≤98.00% to >88.00% | ≤88.00% to >79.68% | ≤79.68% |
| Construction cost performance (QI 1) | >7.98% | ≤7.98% to >0.00% | ≤0.00% to >−3.33% | ≤−3.33% to >−7.92% | ≤−7.92% |
| | >7.93% | ≤7.93% to >0.00% | ≤0.00% to >−2.07% | ≤−2.07% to >−7.91% | ≤−7.91% |
| | >7.96% | ≤7.96% to >0.00% | ≤0.00% to >−2.57% | ≤−2.57% to >−7.91% | ≤−7.91% |
| Construction cost performance (QI 2) | >9.23% | ≤9.23% to >0.00% | ≤0.00% to >−5.87% | ≤−5.87% to >−13.15% | ≤−13.15% |
| | >9.19% | ≤9.19% to >0.00% | ≤0.00% to >−4.27% | ≤−4.27% to >−12.63% | ≤−12.63% |
| | >9.21% | ≤9.21% to >0.00% | ≤0.00% to >−4.80% | ≤−4.80% to >−12.85% | ≤−12.85% |
| Innovation and improvement (QI 1) | <3.95 | ≥3.95 to <5.36 | ≥5.36 to <7.17 | ≥7.17 to <8.20 | ≥8.20 |
| | <3.94 | ≥3.94 to <5.40 | ≥5.40 to <7.17 | ≥7.17 to <8.20 | ≥8.20 |
| | <3.95 | ≥3.95 to <5.38 | ≥5.38 to <7.17 | ≥7.17 to <8.20 | ≥8.20 |
| Innovation and improvement (QI 2) | <1.48% | ≥1.48% to <3.11% | ≥3.11% to <7.01% | ≥7.01% to <8.40% | ≥8.40% |
| | <1.46% | ≥1.46% to <3.01% | ≥3.01% to <7.12% | ≥7.12% to <8.40% | ≥8.40% |
| | <1.47% | ≥1.47% to <3.06% | ≥3.06% to <7.07% | ≥7.07% to <8.40% | ≥8.40% |

Notes: Top fuzzy QR = vertical error method (VEM); middle fuzzy QR = horizontal error method (HEM); and bottom fuzzy QR = bisector error method (BEM).

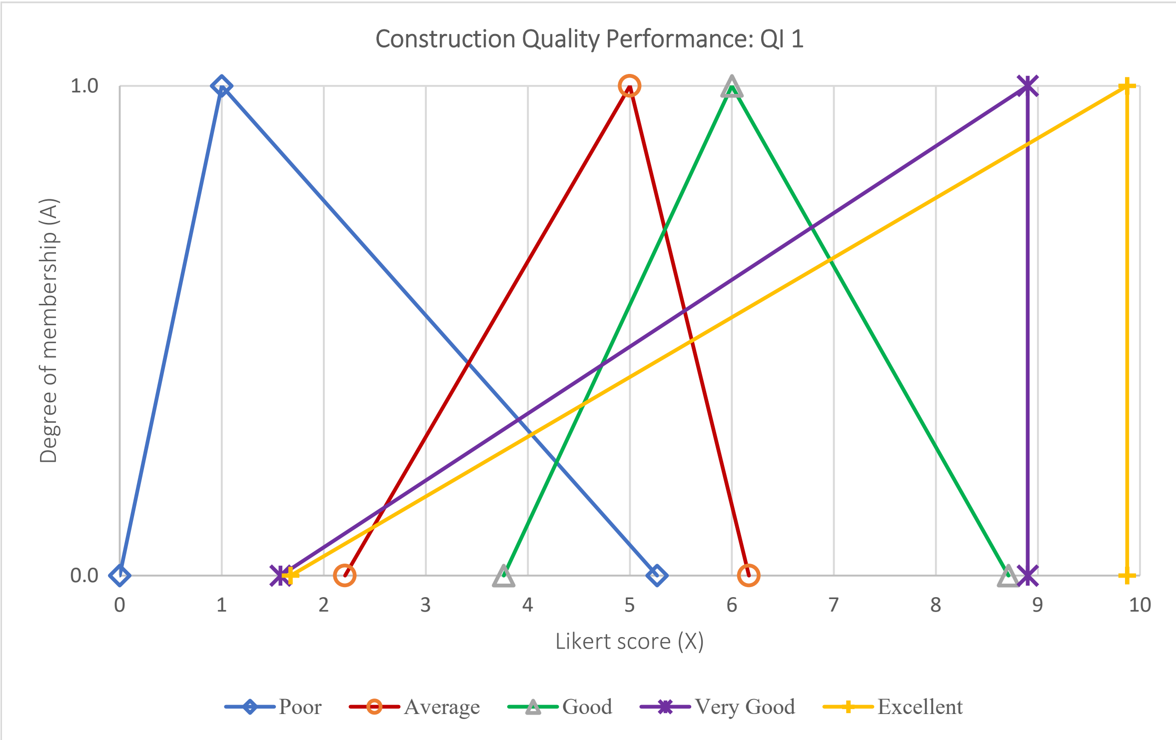
### 3.6. Identification of Fuzzy Membership Functions for the QRs of the QIs

Tables 7 and 8 show the fuzzy QRs of KPIs at the planning and construction phases as well as the post-construction phase of HPs. The underlying fuzzy membership functions of the QIs of construction quality performance are indicated in Figure 3a,b for illustration. The intersection points of successive fuzzy membership functions are used to determine the QRs of QIs, representing the five unique performance levels, namely poor, average, good, very good and excellent. Detailed information on the fuzzy QRs of the QIs for individual KPIs determined by the VEM, HEM and BEM against the five performance levels is used to generate Tables 7 and 8. It can be concluded that the VEM, HEM and BEM produce quite similar results as the deviations are not too much.

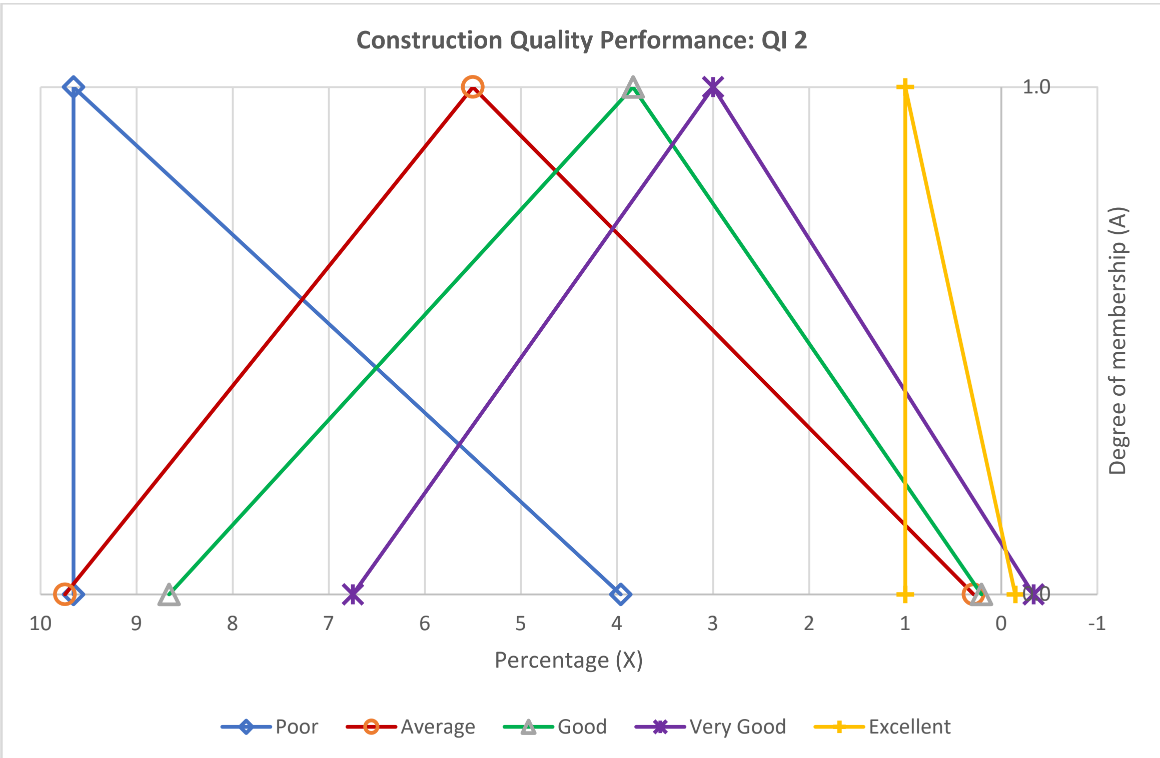
**Table 8.** Fuzzy QRs of the KPIs at the post-construction phase of healthcare projects.

| | Successive Performance Levels | | | | |
|---|---|---|---|---|---|
| | **Poor** | **Average** | **Good** | **Very Good** | **Excellent** |
| Stakeholder/end-user satisfaction (QI 1) | <3.27 | ≥3.27 to <5.00 | ≥5.00 to <7.53 | ≥7.53 to <8.25 | ≥8.25 |
| | <3.14 | ≥3.14 to <5.00 | ≥5.00 to <7.61 | ≥7.61 to <8.29 | ≥8.29 |
| | <3.20 | ≥3.20 to <5.00 | ≥5.00 to <7.57 | ≥7.57 to <8.27 | ≥8.27 |
| Stakeholder/end-user satisfaction (QI 2) | <53.62% | ≥53.62% to <63.16% | ≥63.16% to <74.24% | ≥74.24% to <90.00% | ≥90.00% |
| | <54.38% | ≥54.38% to <63.78% | ≥63.78% to <72.46% | ≥72.46% to <90.00% | ≥90.00% |
| | <54.02% | ≥54.02% to <63.49% | ≥63.49% to <72.99% | ≥72.99% to <90.00% | ≥90.00% |
| Functional suitability (QI 1) | <3.00 | ≥3.00 to <5.44 | ≥5.44 to <6.42 | ≥6.42 to <8.12 | ≥8.12 |
| | <2.93 | ≥2.93 to <5.06 | ≥5.06 to <6.38 | ≥6.38 to <8.14 | ≥8.14 |
| | <2.96 | ≥2.96 to <5.23 | ≥5.23 to <6.39 | ≥6.39 to <8.13 | ≥8.13 |
| Functional suitability (QI 2) | >3.45% | ≤3.45% to >2.68% | ≤2.68% to >1.27% | ≤1.27% to >0.58% | ≤0.58% |
| | >3.52% | ≤3.52% to >2.71% | ≤2.71% to >1.28% | ≤1.28% to >0.58% | ≤0.58% |
| | >3.49% | ≤3.49% to >2.69% | ≤2.69% to >1.28% | ≤1.28% to >0.58% | ≤0.58% |
| Maintenance effectiveness and efficiency (QI 1) | >16.61% | ≤16.61% to >0.00% | ≤0.00% to >−8.60% | ≤−8.60% to >−20.56% | ≤−20.56% |
| | >16.61% | ≤16.61% to >0.00% | ≤0.00% to >−8.60% | ≤−8.60% to >−23.83% | ≤−23.83% |
| | >16.61% | ≤16.61% to >0.00% | ≤0.00% to >−8.60% | ≤−8.60% to >−22.56% | ≤−22.56% |
| Maintenance effectiveness and efficiency (QI 2) | >31.60% | ≤31.60% to >17.14% | ≤17.14% to >11.26% | ≤11.26% to >4.04% | ≤4.04% |
| | >32.69% | ≤32.69% to >17.49% | ≤17.49% to >11.19% | ≤11.19% to >3.55% | ≤3.55% |
| | >32.17% | ≤32.17% to >17.33% | ≤17.33% to >11.22% | ≤11.22% to >3.78% | ≤3.78% |
| Functional capacity and utilization (QI 1) | <63.04% | ≥63.04% to <68.32% | ≥68.32% to <80.00% | ≥80.00% to <90.00% | ≥90.00% |
| | <63.00% | ≥63.00% to <68.68% | ≥68.68% to <80.00% | ≥80.00% to <90.00% | ≥90.00% |
| | <63.02% | ≥63.02% to <68.54% | ≥68.54% to <80.00% | ≥80.00% to <90.00% | ≥90.00% |
| Functional capacity and utilization (QI 2) | <3.16 | ≥3.16 to <5.55 | ≥5.55 to <7.16 | ≥7.16 to <8.14 | ≥8.14 |
| | <3.30 | ≥3.30 to <5.56 | ≥5.56 to <7.21 | ≥7.21 to <8.15 | ≥8.15 |
| | <3.23 | ≥3.23 to <5.55 | ≥5.55 to <7.18 | ≥7.18 to <8.15 | ≥8.15 |
| Flexibility and adaptability of facility (QI 1) | <11.79% | ≥11.79% to <21.91% | ≥21.91% to <31.00% | ≥31.00% to <39.17% | ≥39.17% |
| | <11.51% | ≥11.51% to <21.98% | ≥21.98% to <31.00% | ≥31.00% to <39.17% | ≥39.17% |
| | <11.65% | ≥11.65% to <21.94% | ≥21.94% to <31.00% | ≥31.00% to <39.17% | ≥39.17% |
| Flexibility and adaptability of facility (QI 2) | <2.17 | ≥2.17 to <4.60 | ≥4.60 to <7.38 | ≥7.38 to <8.12 | ≥8.12 |
| | <2.14 | ≥2.14 to <4.61 | ≥4.61 to <7.46 | ≥7.46 to <8.14 | ≥8.14 |
| | <2.15 | ≥2.15 to <4.61 | ≥4.61 to >7.42 | ≥7.42 to <8.13 | ≥8.13 |

Notes: Top fuzzy QR = vertical error method (VEM); middle fuzzy QR = horizontal error method (HEM); and bottom fuzzy QR = bisector error method (BEM).




(**a**)




(**b**)

**Figure 3.** (**a**): Fuzzy membership functions and ranges (QI 1) of performance levels for measuring construction quality performance of HPs. (**b**): Fuzzy membership functions and range (QI 2) of performance levels for measuring construction quality performance of HPs.

As shown in Table 7, for instance, the quality performance of an HP is considered ‘poor’ when the perceived key stakeholders’ satisfaction score with construction quality, using a 10-point Likert scale, is less than 3.42, and excellent when a score of 8.90 and above is recorded. When the cost of rectifying major defects or non-conformances expressed as a percentage of the total project cost is greater than 7.28%, the HP is of poor-quality performance. On the other hand, an excellent project quality performance should not have a cost of rectifying major defects or non-conformance above 1% of the percentage of the total project cost (see Table 7).

## 4. Demonstration of the Fuzzy Success Evaluation Framework

The demonstration of the application of the success evaluation system is based on three hypothetical HPs. Although past studies combined real and hypothetical projects in demonstration [66], the use of only hypothetical HPs is considered reasonable because of constraints of research time and resources. The evaluation of the success levels of real-case HPs in Hong Kong will be considered in a separate study upon developing a computerized system that garners true performance data from the industry. In addition, past studies utilized single QIs for defining considered KPIs [55,56], while two QIs are used in this study (see Tables 7 and 8). The reasons include flexibility in choosing the most appropriate QI for any given HP, use of some or all QIs based on organization's resource level, several optional criteria for comparing success levels of HPs, among others. The use of two QIs could be considered involving because of the larger resource investment, data collection and evaluation process.

Table 9 shows the evaluated performance levels of the HPs using the fuzzy QRs indicated in Tables 7 and 8. Hypothetical Project A: For example, the percentage of EOT with prolongation cost is rated 'excellent' and variation in actual project cost expressed as a percentage of the finally agreed project cost is appraised 'excellent'. At the planning and construction phases, the alternative index with single QIs "#" is 2.918 (good), the alternative index with single QIs "*" is 4.103 (very good) and the alternative index with both QIs is 3.511 (very good). At the post-construction phase, the alternative index with single QIs "#" is 4.206 (very good), the alternative index with single QIs "*" is 5.000 (excellent) and the alternative index with both QIs is 4.603 (excellent). For the combined project phases, the alternative index with single QIs "#" is 3.562 (very good), the alternative index with single QIs "*" is 4.552 (excellent) and the alternative index with both QIs is 4.057 (very good).

Hypothetical Project B: For instance, the cost saving through innovation is judged excellent and the percentage of facilities categorized as satisfactory in terms of amenity and comfort engineering is graded 'excellent'. At the planning and construction phases, the alternative index with single QIs "#" is 4.545 (excellent), the alternative index with single QIs "*" is 4.806 (excellent) and the alternative index with both QIs is 4.676 (excellent). At the post-construction phase, the alternative index with single QIs "#" is 4.302 (very good), the alternative index with single QIs "*" is 4.777 (excellent) and the alternative index with both QIs is 4.540 (excellent). For the combined project phases, the alternative index with single QIs "#" is 4.424 (very good), the alternative index with single QIs "*" is 4.792 (excellent) and the alternative index with both QIs is 4.608 (excellent).

Hypothetical Project C: To illustrate, the ratio of the expenditure on unplanned maintenance to the cost value of planned maintenance is scored as 'average' and the percentage of the UFA of a building that is devoted to multiple or newer usages is assessed as 'poor'. At the planning and construction phases, the alternative index with single QIs "#" is 2.144 (average), the alternative index with single QIs "*" is 2.050 (average) and the alternative index with both QIs is 2.097 (average). At the post-construction phase, the alternative index with single QIs "#" is 3.073 (good), the alternative index with single QIs "*" is 2.651 (good) and the alternative index with both QIs is 2.862 (good). For the combined project phases, the alternative index with single QIs "#" is 2.609 (good), the alternative index with single QIs "*" is 2.351 (average) and the alternative index with both QIs is 2.480 (average).

**Table 9.** Exemplification of success evaluation with the QIs of KPIs using hypothetical healthcare projects.

| | | **Project A (Cost: HKD 1.5 billion; Duration: 45 months; Procurement system: Construction management; Project size: 750 beds; Tendering method: Negotiated tendering; Project phase: 9 years post-construction)** | | | | | **Project B (Cost: HKD 850 million; Duration: 24 months; Procurement system: Sequential traditional; Project size: 400 beds; Tendering method: Selective tendering; Project phase: 5 years post-construction)** | | | | | **Project C (Cost: HKD 1.05 billion; Duration: 30 months; Procurement system: Novated design and build; Project size: 550 beds; Tendering method: Negotiated tendering; Project phase: 12 years post-construction)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Weighting** | **Rating** | **Label** | **Score** | **Index** | **Average Index** | **Rating** | **Label** | **Score** | **Index Value** | **Average Index** | **Rating** | **Label** | **Score** | **Index** | **Average Index** |
| KPI 1: Construction quality performance | | | | | | | | | | | | | | | | |
| QI 1 | 0.229 | 7.8 | Very good | 4 | * 0.915 | 0.687 | 9.0 | Excellent | 5 | * 1.144 | 1.030 | 5.7 | Good | 3 | * 0.687 | 0.458 |
| QI 2 | 0.229 | 6.2% | Average | 2 | # 0.458 | | 2.8% | Very good | 4 | # 0.915 | | 12.2% | Poor | 1 | # 0.229 | |
| KPI 2: Construction time performance | | | | | | | | | | | | | | | | |
| QI 1 | 0.204 | 0% | Good | 3 | # 0.611 | 0.815 | −10.5% | Excellent | 5 | # 1.019 | 1.019 | 4.5% | Average | 2 | # 0.408 | 0.408 |
| QI 2 | 0.204 | 0.8% | Excellent | 5 | * 1.019 | | 1.1% | Excellent | 5 | * 1.019 | | 8.6% | Average | 2 | * 0.408 | |
| KPI 3: Construction safety performance | | | | | | | | | | | | | | | | |
| QI 1 | 0.226 | 96.1% | Good | 3 | # 0.677 | 0.790 | 82.0% | Very good | 4 | # 0.903 | 1.016 | 93.4% | Good | 3 | # 0.677 | 0.451 |
| QI 2 | 0.226 | 85.0% | Very Good | 4 | * 0.903 | | 60.5% | Excellent | 5 | * 1.129 | | 126.0% | Poor | 1 | * 0.226 | |
| KPI 4: Construction cost performance | | | | | | | | | | | | | | | | |
| QI 1 | 0.194 | −11.4% | Excellent | 5 | * 0.972 | 0.777 | −5.8% | Very good | 4 | * 0.777 | 0.875 | −1.3% | Good | 3 | * 0.583 | 0.486 |
| QI 2 | 0.194 | −1.8% | Good | 3 | # 0.583 | | −16.0% | Excellent | 5 | # 0.972 | | 3.7% | Average | 2 | # 0.389 | |
| KPI 5: Innovation and improvement | | | | | | | | | | | | | | | | |
| QI 1 | 0.147 | 7.7 | Very good | 4 | # 0.589 | 0.442 | 8.6 | Excellent | 5 | # 0.737 | 0.737 | 6.7 | Good | 3 | # 0.442 | 0.295 |
| QI 2 | 0.147 | 2.5% | Average | 2 | * 0.295 | | 11.5% | Excellent | 5 | * 0.737 | | 0.6% | Poor | 1 | * 0.147 | |
| PACP 1: Alternative index with single QIs | | | | | # 2.918 | | | | | # 4.545 | | | | | # 2.144 | |
| PACP 2: Alternative index with single QIs | | | | | * 4.103 | | | | | * 4.806 | | | | | * 2.050 | |
| PACP 3: Alternative index with both QIs | | | | | | 3.511 | | | | | 4.676 | | | | | 2.097 |
| KPI 6: Stakeholder/end-user satisfaction | | | | | | | | | | | | | | | | |
| QI 1 | 0.236 | 9.7 | Excellent | 5 | # 1.179 | 1.179 | 9.1 | Excellent | 5 | # 1.179 | 1.179 | 6.9 | Good | 3 | # 0.708 | 0.826 |
| QI 2 | 0.236 | 95.0% | Excellent | 5 | * 1.179 | | 93.6% | Excellent | 5 | * 1.179 | | 84.5% | Very good | 4 | * 0.944 | |

**Table 9.** *Cont.*

| | | **Project A (Cost: HKD 1.5 billion; Duration: 45 months; Procurement system: Construction management; Project size: 750 beds; Tendering method: Negotiated tendering; Project phase: 9 years post-construction)** | | | | | **Project B (Cost: HKD 850 million; Duration: 24 months; Procurement system: Sequential traditional; Project size: 400 beds; Tendering method: Selective tendering; Project phase: 5 years post-construction)** | | | | | **Project C (Cost: HKD 1.05 billion; Duration: 30 months; Procurement system: Novated design and build; Project size: 550 beds; Tendering method: Negotiated tendering; Project phase: 12 years post-construction)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Weighting** | **Rating** | **Label** | **Score** | **Index** | **Average Index** | **Rating** | **Label** | **Score** | **Index Value** | **Average Index** | **Rating** | **Label** | **Score** | **Index** | **Average Index** |
| KPI 7: Functional suitability | | | | | | | | | | | | | | | | |
| QI 1 | 0.223 | 7.4 | Very good | 4 | # 0.890 | 1.002 | 9.0 | Excellent | 5 | # 1.113 | 1.002 | 5.7 | Good | 3 | # 0.668 | 0.445 |
| QI 2 | 0.223 | 0.3% | Excellent | 5 | * 1.113 | | 1.2% | Very good | 4 | * 0.890 | | 4.5% | Poor | 1 | * 0.223 | |
| KPI 8: Maintenance effectiveness and efficiency | | | | | | | | | | | | | | | | |
| QI 1 | 0.199 | −13.5% | Very good | 4 | # 0.797 | 0.897 | −18.3% | Very good | 4 | # 0.797 | 0.897 | −9.2% | Very good | 4 | # 0.797 | 0.598 |
| QI 2 | 0.199 | 2.0% | Excellent | 5 | * 0.997 | | 2.7% | Excellent | 5 | * 0.997 | | 25.8% | Average | 2 | * 0.399 | |
| KPI 9: Functional capacity and utilization | | | | | | | | | | | | | | | | |
| QI 1 | 0.186 | 94.5% | Excellent | 5 | * 0.930 | 0.744 | 90.0% | Excellent | 5 | * 0.930 | 0.837 | 98.2% | Excellent | 5 | * 0.930 | 0.837 |
| QI 2 | 0.186 | 6.3 | Good | 3 | # 0.558 | | 8.0 | Very good | 4 | # 0.744 | | 7.7 | Very good | 4 | # 0.744 | |
| KPI 10: Flexibility and adaptability of facility | | | | | | | | | | | | | | | | |
| QI 1 | 0.156 | 45.2% | Excellent | 5 | * 0.781 | 0.781 | 54.5% | Excellent | 5 | * 0.781 | 0.625 | 4.0% | Poor | 1 | * 0.156 | 0.156 |
| QI 2 | 0.156 | 9.4 | Excellent | 5 | # 0.781 | | 6.4 | Good | 3 | # 0.468 | | 1.5 | Poor | 1 | # 0.156 | |
| PCP 1: Alternative index with single QIs | | | | | # 4.206 | | | | | # 4.302 | | | | | # 3.073 | |
| PCP 2: Alternative index with single QIs | | | | | * 5.000 | | | | | * 4.777 | | | | | * 2.651 | |
| PCP 3: Alternative index with both QIs | | | | | | 4.603 | | | | | 4.540 | | | | | 2.862 |
| CPP 1: Alternative index with single QIs | | | | | # 3.562 | | | | | # 4.424 | | | | | # 2.609 | |
| CPP 2: Alternative index with single Qis | | | | | * 4.552 | | | | | * 4.792 | | | | | * 2.351 | |
| CPP 3: Alternative index with both QIs | | | | | | 4.057 | | | | | 4.608 | | | | | 2.480 |

Notes: PACP = planning and construction phases; PCP = post-construction phase; CPP = combined project phases; the signs * or # = optional choice between the two QIs of each KPI.

Generally, the comparative success levels are in the descending order of Project B, Project A and Project C during the planning and construction phases. Considering the post-construction phase, the top-down order of success levels is Project A, Project B and Project C. The combined project phases manifest Project B as the most successful, followed by Project A and then Project C. These comparative results of the alternative success indexes across the life cycle phases of HPs are further visualized with a spider diagram (see Figure 4).

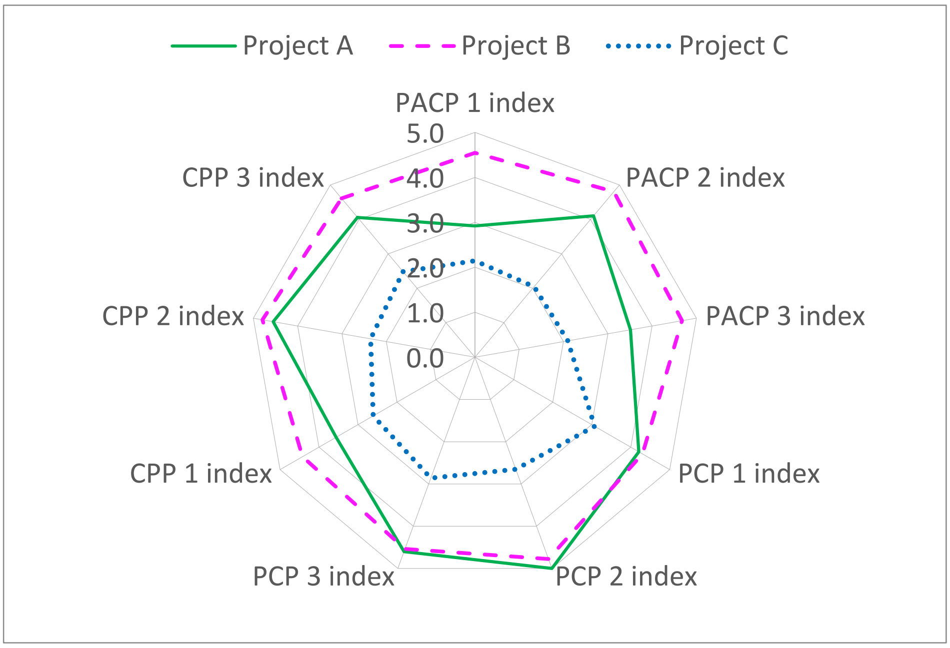



**Figure 4.** Comparison of phase-based success levels across three healthcare projects.

## 5. Discussion

Construction-related activities in the planning, construction, and post-construction phases of HPs are essential to achieving fundamental outcomes at the project, organization and societal levels. This study demystifies the life cycle success of HPs by establishing objective metrics for evaluating ten selected KPIs, namely, time performance, cost performance, quality performance, safety performance, innovation and improvement, stakeholder/end-user satisfaction, functional suitability, maintenance effectiveness and efficiency, functional capacity and utilization, and flexibility and adaptability, which are foundational for achieving the triple bottom line of sustainability (i.e., social, economic and environmental dimensions) in the healthcare sector. For example, 'flexibility and adaptability' measures how easily a healthcare facility can adjust to meet additional user demands, preventing expansions and extending the facility's lifespan, thereby supporting a circular economy [67–70]. With environmental sustainability becoming the standard in healthcare [71,72], 'innovation and improvement' could focus on innovation in reuse, recycling, and reducing resource consumption, as well as tracking carbon emissions to monitor greenhouse gases from HPs.

The adopted methodology has limited application in the performance measurement of general construction projects, and much less of HPs. Yeung et al. [55] conducted a research work on measuring the performance of relationship-based construction projects in Australia. Time performance, cost performance and innovation and improvement were similar KPIs established for metrics development. In terms of construction time performance, HPs are poor with an overrun of more than 10% and excellent with an underrun of at least 7.74%, as compared to partnering projects that are poor with above 3.8% overrun and excellent with at least 12% underrun. For cost performance, HPs perform poorly with an overrun exceeding 7.96% and excellently with an underrun equal to or more than 7.91%, contrasting with partnering projects that perform poorly if the overrun is greater than 5.8% and excellently if the underrun is 10.7% or more. In Hong Kong partnering construction projects, time performance is defined as poor by experiencing overrun in excess of 2.6% and excellent by witnessing an underrun of at least 10.3%, while cost performance is attested to be poor with an overrun above 2.9% and excellent with an underrun more than or equal to 10.4% [62].

Considering innovation and improvement, HPs attain poor performance with cost saving % below 1.47% and excellent performance with cost saving % of at least 8.40%. Additionally, key stakeholders' satisfaction Likert score lower than 3.95 represents poor performance and a minimum of 8.20 denotes excellent performance of innovation and improvement in HPs. In comparison, innovation and improvement are deemed to perform poorly in partnering projects where the cost saving % is less than 0.6% and excellently where the cost saving % is equal to or more than 9.6% [62]. In addition, innovation and improvement are regarded as poor when the key stakeholders score is under 3.3 and excellent when the score is at least 8.5 in relationship-based projects [55]. Construction safety performance and construction quality performance were also selected for assessing partnering and relationship-based projects but with uniquely different metrics. Generally, HPs are more flexible and accommodating in terms of the requirements of performance thresholds when compared to partnering and relationship-based projects. This can be explained by the unique features and characteristics of HPs such as rapidly changing regulatory laws, the top-most standard in healthcare value delivery, complex and dynamic implementation procedures, great technological needs, several statutory permitting processes, and contradictory expectations of stakeholders [5,6]. Accordingly, performance expectations are high, and HPs are uncommonly difficult to plan, construct and operate. The uniqueness of HPs requires various experienced specialist sub-contractors, clients, consultants, stakeholders and main contractors to be extensively involved in the successive life cycle phases to contribute to top-notch performance.

Presently, HPs are only compared to general relationship-based projects and partnering projects by strictly following the framework of evaluation. However, there will be a need to compare HPs to proper types of projects, e.g., school projects, commercial projects, housing projects, etc. to derive the true value of the evaluation framework. In addition, scholarly works must focus attention on performance assessment with relevant KPIs at post-construction phase HPs.

### *5.1. Recommendations*

The study developed a novel success evaluation framework for HPs in Hong Kong based on the opinions of experts in HPs. Based on the findings, some practical implications of the research findings are provided to enhance the performance of HPs.

The study established objective metrics of selected KPIs for defining the success of HPs across the life cycle phases. First, it is important to devise a continuous monitoring and periodic evaluation of HP performance using the established KPIs. Through this approach, potential issues that could hinder achieving the continual performance of HPs can be quickly identified, and remedial or corrective actions can be taken promptly. The information received in the monitoring and evaluation of HPs at any phase could be stored in a databank for improvement on the success evaluation model of future projects.

HPs in Hong Kong are found to need some attention to reduce the number of accidents per assessment period. Hence, enforcement of safety protocols and measures in construction sites is required for the wellbeing of construction workers, professionals and other stakeholders. Construction workers and professionals should continuously be trained on the required safety regulations on construction sites. A significant number of construction workers are ethnic minorities who may not understand safety instructions written in Chinese. Therefore, it is important to write safety instructions in the English language or the local language of most foreign construction workers, and the foreman should be reminded to update workers with safety information regularly. On the other hand, ethnic minority construction workers should be encouraged to learn the native language of Hong Kong.

Despite the global recognition of the successes of the Hong Kong construction industry, HPs require more effort investment to reach impeccable standards in terms of time, cost and quality performance. Therefore, it is advised to provide contingency planning to mitigate any unforeseen circumstances that may affect the delivery of HPs on time [73]. The re-measurement of elements of work executed using the contingency sum provided would also contribute to the cost performance of HPs.

Based on the results of the success evaluation model of HPs for the post-construction phase, it is recommended that a user-centric design should be continually maintained to further enhance stakeholder/end-user satisfaction. The end-users of healthcare facilities should also be engaged at the planning phase to receive extensive opinions necessary for the functional suitability of the projects. In addition, a scalable plan for future development, changes and growth in healthcare demand can also be considered in HP development. The overall performance data obtained at the post-construction phase of all HPs can be benchmarked for best practices, continuous learning within project teams and decision-making on future HPs.

### *5.2. Theoretical Contributions*

The study contributes theoretically to the literature on pragmatic KPIs of HPs. The 10 KPIs used in the study were previously established by top experts through multiple rounds of Delphi surveys. Drawing on the study participants' selection of the fundamental performance metrics for HPs, the findings can be compared with those of future studies in both developing and developed nations. The findings enrich the theoretical framework of HPs and the associated KPIs for successful project delivery. The use of a soft computing approach reduces fuzzy bias in the success evaluation model which enriches the theoretical construct of the study. The findings can be useful for HP stakeholders, namely government, construction professionals, medical practitioners and society at large, to enhance the outcomes of healthcare facilities.

### *5.3. Limitations of the Study*

Although the study achieved the intended objectives, some limitations are noticeable. There is a lack of universally agreed-upon KPIs for evaluating the success of HPs. Therefore, future studies can investigate KPIs and corresponding metrics that define successful HPs in other regions for comparison with current findings. Thereafter, standardized performance evaluation of HPs can be conducted. This study evaluated the HP success index for the post-construction phase. However, there is a need to address the complete lifecycle phase of HPs, with a clear focus on the demolition and deconstruction phase for sustainability. In addition, it is required to consistently update KPIs to meet the changing expectations of HP stakeholders and the evolving characteristics of HPs.

## 6. Conclusions

In this study, a success evaluation framework is developed for HPs by using Hong Kong as a case study. Through the analysis of questionnaire survey data gathered from an expert panel with fuzzy set theory (i.e., BEM), the study evaluates indexes comprising selected KPIs of the HP life cycle by establishing corresponding objective, reliable and practical scales as performance levels or grades. The performance grades are ranges of metric values on scales constituting the appropriate definitions of 'poor', 'average', 'good', 'very good' and 'excellent' performance. The underlying KPIs of the framework are construction quality performance, construction time performance, construction safety performance, construction cost performance, and innovation and improvement for the planning and construction phases, and stakeholder/end-user satisfaction, functional suitability, maintenance effectiveness and efficiency, functional capacity and utilization, and flexibility and adaptability of the facility for the post-construction phase of HPs. These KPIs pertain to the triple bottom line of sustainability for sustainable development in healthcare facilities or the construction of HPs. The framework is demonstrated on three hypothetical HPs to establish objective, reliable and practical outcomes for performance comparison, benchmarking and improvement purposes.

The findings have practical implications for policymakers and practitioners. The framework of KPIs and metrics is foundational in decision-making. Policymakers can track the performance of HPs by linking the KPIs and metrics to goals, targets and ultimately to policy priorities. Indeed, policymaking is not enough, but assessing the outcomes of such policies is paramount to evaluating the policies for improvement towards tactical and strategic goals in the quest for sustainable development. Such policy assessment is achieved through the KPIs and robust objective metrics established in this study. In addition, the framework is instrumental for consolidating relevant performance assessment outcomes of HPs into a robust database for comparison and benchmarking in the construction industry. Moreover, these KPIs could be incorporated into regulations by the appropriate authorities to influence how designers and construction companies implement HPs.

**Author Contributions:** Conceptualization, A.P.C.C., M.W.C. and A.D.; Data curation, G.D.O.; Formal analysis, G.D.O.; Funding acquisition, A.P.C.C., M.W.C. and A.D.; Investigation, G.D.O.; Methodology, A.P.C.C., M.W.C. and A.D.; Project administration, M.W.C. and A.D.; Supervision, A.P.C.C.; Validation, A.P.C.C., M.W.C. and A.D.; Visualization, G.D.O. and M.A.A.; Writing—original draft, G.D.O., M.A.A. and L.D.O.; Writing—review and editing, A.P.C.C. and A.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This paper is part of the Research Grants Council (RGC) funded study "Developing a computerized project success index system to monitor and benchmark the performance of hospital projects" (RGC General Research Fund: 15205421). Accordingly, this paper shares similar background and literature, but dissimilar scope, objectives and outcomes with other papers that have been/may be published elsewhere.

**Institutional Review Board Statement:** Ethical review and approval were waived for this study due to the study involving anonymous data collection.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The raw data supporting the conclusions of this article will be made available by the authors on request.

**Acknowledgments:** The authors would like to appreciate the Delphi experts who contributed their HP experiences to the study.

**Conflicts of Interest:** There is no conflict of interest.

## Appendix A

**Table A1.** Formulae for computing the selected QIs of the KPIs.

| No. | Quantitative Indicators (QIs) | Formula |
|---|---|---|
| | KPI 1: Construction quality performance | |
| QI 1 | Perceived key stakeholders' satisfaction scores with construction quality by using Likert scale. | Ten-point Likert scale: Least satisfied (1) to absolutely satisfied (10) |
| QI 2 | Cost of rectifying major defects or non-conformances of a project expressed as a % of total project cost. | $= \frac{\text{Cost of rectifying major defects or non}-\text{conformances}}{\text{Total project } \cos\text{t}} \times 100\%$ |
| | KPI 2: Construction time performance | |
| QI 1 | % variation between actual completion time and finally agreed completion time | $= \frac{\text{Actual completion time}-\text{Finally agreed completion time}}{\text{Finally agreed completion time}} \times 100\%$ |
| QI 2 | % of EOT with prolongation cost (i.e., ratio of extension of time [EOT] with prolongation cost to finally agreed completion time). | $= \frac{\text{Extension of time (EOT) with prolongation } \cos\text{t}}{\text{Finally agreed completion time}} \times 100\%$ |
| | KPI 3: Construction safety performance | |
| QI 1 | Number of accidents per assessment period (e.g., man-hours) (expressed in %) | $= \frac{\text{Specific project accident rate in man}-\text{hours}}{\text{Current (hospital) industry accident rate in man}-\text{hours}} \times 100\%$ |
| QI 2 | Number of reportable accidents per 1000 workers in project (expressed in %) | $= \frac{\text{Specific project reportable accident rate per 1000 workers}}{\text{Current (hospital) industry reportable accident rate per 1000 workers}} \times 100\%$ |
| | KPI 4: Construction cost performance | |
| QI 1 | Variation in actual project cost expressed as a % of finally agreed project cost. | $= \frac{\text{Actual project } \cos\text{t}-\text{Finally agreed project } \cos\text{t}}{\text{Finally agreed project } \cos\text{t}} \times 100\%$ |
| QI 2 | Variation in actual project cost expressed as a % of project cost at contract award. | $= \frac{\text{Actual project } \cos\text{t}-\text{Project } \cos\text{t at contract award}}{\text{Project } \cos\text{t at contract award}} \times 100\%$ |
| | KPI 5: Innovation and improvement | |
| QI 1 | Perceived key stakeholders' satisfaction scores by using Likert scale. | Ten-point Likert scale: Least satisfied (1) to absolutely satisfied (10) |
| QI 2 | Cost saving through innovation (i.e., % of the total project cost saved due to innovation initiatives introduced) | $= \frac{\text{Innovation } \cos\text{t savings}}{\text{Total project } \cos\text{t}} 100\%$ |
| | KPI 6: Stakeholder/end-user satisfaction | |
| QI 1 | Results of post occupancy evaluation (POE) scored by using Likert scale. | Ten-point Likert scale: Least satisfied (1) to absolutely satisfied (10) |
| QI 2 | % of facilities categorized as satisfactory in terms of amenity and comfort engineering (expressed in terms of usable floor area [UFA]). | $= \frac{\text{UFA of facility spaces categorized as satisfactory regarding amenity and comfort engineering}}{\text{Total UFA of facility spaces}} 100\%$ |
| | KPI 7: Functional suitability | |
| QI 1 | Degree to which the functions (of building and its components) facilitate the accomplishment of specified tasks and objectives (expressed in Likert scale). | Ten-point Likert scale: Least satisfied (1) to absolutely satisfied (10) |
| QI 2 | Cost of modifications of facilities to meet relevant functional requirements as part of the current plan (expressed in %). | $= \frac{\text{Annual modification cost of facilities to meet functional requirements}}{\text{Current replacement value (CRV)}} \times 100\%$ |
| | KPI 8: Maintenance effectiveness and efficiency | |
| QI 1 | Variation in actual maintenance expenditure expressed as a % of available maintenance budget in a year. | $= \frac{\text{Annual maintenance expenditure}-\text{Annual maintenance budget}}{\text{Annual maintenance budget}} \times 100\%$ |
| QI 2 | Ratio of the expenditure on unplanned maintenance to the cost value of planned maintenance across the assessment period (expressed in %). | $= \frac{\text{Annual expenditure on unplanned maintenance}}{\text{Annual } \cos\text{t value of planned maintenance}} 100\%$ |

**Table A1.** *Cont.*

| No. | Quantitative Indicators (QIs) | Formula |
| --- | --- | --- |
| | KPI 9: Functional capacity and utilization | |
| QI 1 | % of properties categorized as fully used (expressed in terms of usable floor area [UFA]). | $= \frac{\text{UFA of properties categorized as fully used}}{\text{Total UFA of properties}}\ 100\%$ |
| QI 2 | Perceived key stakeholders' satisfaction scores by using Likert scale | Ten-point Likert scale: Least satisfied (1) to absolutely satisfied (10) |
| | KPI 10: Flexibility and adaptability of facility | |
| QI 1 | % of the usable floor area (UFA) of building that is devoted to multiple or newer usage across the assessment period. | $= \frac{\text{UFA of building devoted to multiple or newer usage}}{\text{Total UFA of building}}\ 100\%$ |
| QI 2 | Possibility of adapting building and its installation systems easily to accommodate additional demands from the end-user (expressed in Likert scale). | Ten-point Likert scale: Least satisfied (1) to absolutely satisfied (10) |

## References


1. GlobalData. Project Insight: Global Healthcare Construction Projects (Q2 2024). GlobalData. 2024. Available online: https://www.globaldata.com/store/report/healthcare-construction-projects-market-analysis/ (accessed on 6 August 2024).
2. Organisation for Economic Co-operation and Development (OECD). Investing in Health Systems to Protect Society and Boost the Economy: Priority Investments and Order-of-Magnitude Cost Estimates. 2022. Available online: https://www.oecd.org/en/publications/investing-in-health-systems-to-protect-society-and-boost-the-economy-priority-investments-and-order-of-magnitude-cost-estimates-abridged-version_94ba313a-en/full-report.html (accessed on 22 January 2025).
3. World Health Organization. *World Health Statistics 2019: Monitoring Health for the SDGs, Sustainable Development Goals*; World Health Organization: Geneva, Switzerland, 2019.
4. United Nations. *World Population Prospects 2024: Summary of Results*; UN DESA/POP/2024; United Nations, Department of Economic and Social Affairs, Population Division: New York, NY, USA, 2024.
5. Sharma, V.; Caldas, C.H.; Mulva, S.P. Development of metrics and an external benchmarking program for healthcare facilities. *Int. J. Constr. Manag.* **2021**, *21*, 615–630. [CrossRef]
6. Soliman-Junior, J.; Tzortzopoulos, P.; Baldauf, J.P.; Pedo, B.; Kagioglou, M.; Formoso, C.T.; Humphreys, J. Automated compliance checking in healthcare building design. *Autom. Constr.* **2021**, *129*, 103822. [CrossRef]
7. Lavy, S.; Garcia, J.A.; Dixit, M.K. KPIs for facility's performance assessment, Part I: Identification and categorization of core indicators. *Facilities* **2014**, *32*, 256–274. [CrossRef]
8. Rosacker, K.M.; Zuckweiler, K.M.; Buelow, J.R. An Empirical Evaluation of Hospital Project Implementation Success. *Acad. Health Care Manag. J.* **2010**, *6*, 37–53.
9. Ling, F.Y.Y.; Li, Q. Managing the Development & Construction of Public Hospital Projects. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Bristol, UK, February 2019; Volume 471, p. 022001. [CrossRef]
10. Adamy, A.; Abu Bakar, A.H. Developing a building-performance evaluation framework for post-disaster reconstruction: The case of hospital buildings in Aceh, Indonesia. *Int. J. Constr. Manag.* **2021**, *21*, 56–77. [CrossRef]
11. Cho, M. Evaluating therapeutic healthcare environmental criteria: Architectural designers' perspectives. *Int. J. Environ. Res. Public Health* **2023**, *20*, 1540. [CrossRef] [PubMed]
12. Adamy, A. Disaster-Resilient Building: Lesson Learned from a Building Performance Evaluation of Meuraxa Hospital in Aceh, Indonesia. In *Resilient and Responsible Smart Cities*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 179–193. [CrossRef]
13. Gimbert, X.; Bisbe, J.; Mendoza, X. The role of performance measurement systems in strategy formulation processes. *Long Range Plan.* **2010**, *43*, 477–497. [CrossRef]
14. Ahmad, H.; Abdul Aziz, A.R.; Jaafar, M. Success criteria for design-and-build public hospital construction project in Malaysia: An empirical study. *Appl. Mech. Mater.* **2015**, *749*, 410–414. [CrossRef]
15. Adamy, A.; Abu Bakar, A.H. Key criteria for post-reconstruction hospital building performance. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Pahang Pekan, Malaysia, 31 October 2019; Volume 469, p. 012072. [CrossRef]
16. Lavy, S.; Garcia, J.A.; Dixit, M.K. KPIs for facility's performance assessment, Part II: Identification of variables and deriving expressions for core indicators. *Facilities* **2014**, *32*, 275–294. [CrossRef]
17. Buelow, J.R.; Zuckweiler, K.M.; Rosacker, K.M. Evaluation methods for hospital projects. *Hosp. Top.* **2010**, *88*, 10–17. [CrossRef] [PubMed]

18. Lai, J.; Yuen, P.L. Identification, classification and shortlisting of performance indicators for hospital facilities management. *Facilities* **2021**, *39*, 4–18. [CrossRef]
19. Wai, S.H.; Aminah, M.Y.; Syuhaida, I. Social infrastructure project success criteria–An exploratory study. *Int. J. Constr. Manag.* **2013**, *13*, 95–104. [CrossRef]
20. Iskandar, K.A.; Hanna, A.S.; Lotfallah, W. Modeling the performance of healthcare construction projects. *Eng. Constr. Archit. Manag.* **2019**, *26*, 2023–2039. [CrossRef]
21. WCCF. The Creative Economy: A Cornerstone Of Hong Kong's Future. World Cities Culture Forum. 2024. Available online: https://worldcitiescultureforum.com/city/hong-kong/#:~:text=Today,%20Hong%20Kong%20stands%20as,whom%20are%20of%20Chinese%20descent (accessed on 20 August 2024).
22. International Trade Administration. Hong Kong: Healthcare. International Trade Administration. 2024. Available online: https://www.trade.gov/country-commercial-guides/hong-kong-healthcare#:~:text=Hong%20Kong%20has%20started%20two,budgeted%20at%20US$38.4%20billion (accessed on 21 August 2024).
23. Hospital Authority. Introduction. Hospital Authority. 2024. Available online: https://www.ha.org.hk/visitor/ha_visitor_index.asp?Content_ID=10008&Lang=ENG&Dimension=100&Parent_ID=10004 (accessed on 20 August 2024).
24. Schoeb, V. Healthcare Service in Hong Kong and its Challenges. *China Perspect.* **2016**, *4*, 51–58. [CrossRef]
25. Legislative Council Panel on Health Services (LCPHS). Second Ten-year Hospital Development Plan. LC Paper No. CB (2)1167/18-19(07), Hong Kong Government, Hong Kong. 2019. Available online: https://www.legco.gov.hk/yr18-19/english/panels/hs/papers/hs20190415cb2-1167-7-e.pdf (accessed on 4 April 2023).
26. Legislative Council Panel on Health Services (LCPHS). The First and Second 10-year Hospital Development Plan. LC Paper No. CB (4)600/20-21(08), Hong Kong Government, Hong Kong. 2021. Available online: https://www.legco.gov.hk/yr20-21/english/panels/hs/papers/hs20210312cb4-600-8-e.pdf (accessed on 21 August 2024).
27. Chan, A.P.C.; Chan, E.H.W.; Chan, A.P.L. Managing Health Care Projects in Hong Kong: A Case Study of the North District Hospital. *Int. J. Constr. Manag.* **2003**, *3*, 1–13. [CrossRef]
28. Chan, A.P.L.; Chan, A.P.C.; Chan, D.W.M. A study of managing healthcare projects in Hong Kong. In Proceedings of the 19th Annual ARCOM Conference, Brighton, UK, 3–5 September 2003; Greenwood, D.J., Ed.; University of Brighton: Brighton, UK; Association of Researchers in Construction Management: Leeds, UK, 2003; Volume 2, pp. 513–522.
29. Al-Tmeemy, S.M.H.M.; Abdul-Rahman, H.; Harun, Z. Future criteria for success of building projects in Malaysia. *Int. J. Proj. Manag.* **2011**, *29*, 337–348. [CrossRef]
30. Chan, A.P.L. Critical Success Factors for Delivering Healthcare Projects in Hong Kong. Ph.D. Thesis, Department of Building and Real Estate, Hong Kong Polytechnic University, Hong Kong, China, 2004.
31. Zuo, J.; Zillante, G.; Zhao, Z.Y.; Xia, B. Does project culture matter? A comparative study of two major hospital projects. *Facilities* **2014**, *32*, 801–824. [CrossRef]
32. Gokhale, S.; Gormley, T.C. *Construction Management of Healthcare Projects*; McGraw-Hill Education: Columbus, OH, USA, 2014.
33. Do, D.; Ballard, G.; Tillmann, P. *Part 1 of 5: The Application of Target Value Design in the Design and Construction of the UHS Temecula Valley Hospital*; Project Production Systems Laboratory, University of California: Berkeley, CA, USA, 2015.
34. Choi, J.; Leite, F.; de Oliveira, D.P. BIM-based benchmarking system for healthcare projects: Feasibility study and functional requirements. *Autom. Constr.* **2018**, *96*, 262–279. [CrossRef]
35. Talib, Y.; Yang, R.J.; Rajagopalan, P. Evaluation of building performance for strategic facilities management in healthcare: A case study of a public hospital in Australia. *Facilities* **2013**, *31*, 681–701. [CrossRef]
36. Edum-Fotwe, F.T.; Egbu, C.; Gibb, A.G.F. Designing facilities management needs into infrastructure projects: Case from a major hospital. *J. Perform. Constr. Facil.* **2003**, *17*, 43–50. [CrossRef]
37. Shohet, I.M. Key performance indicators for strategic healthcare facilities maintenance. *J. Constr. Eng. Manag.* **2006**, *132*, 345–352. [CrossRef]
38. Choi, J.; Leite, F.; de Oliveira, D.P. BIM-based benchmarking for healthcare construction projects. *Autom. Constr.* **2020**, *119*, 103347. [CrossRef]
39. Lai, J.H.; Hou, H.C.; Chiu, B.W.; Edwards, D.; Yuen, P.L.; Sing, M.; Wong, P. Importance of hospital facilities management performance indicators: Building practitioners' perspectives. *J. Build. Eng.* **2022**, *45*, 103428. [CrossRef]
40. Lai, J.H.; Hou, H.C.; Edwards, D.J.; Yuen, P.L. An analytic network process model for hospital facilities management performance evaluation. *Facilities* **2021**, *40*, 333–352. [CrossRef]
41. Li, Y.; Cao, L.; Han, Y.; Wei, J. Development of a conceptual benchmarking framework for healthcare facilities management: Case study of shanghai municipal hospitals. *J. Constr. Eng. Manag.* **2020**, *146*, 05019016. [CrossRef]
42. Omar, M.F.; Ibrahim, F.A.; Omar, W.M.S.W. Key performance indicators for maintenance management effectiveness of public hospital building. In Proceedings of the MATEC Web of Conferences, Les Ulis, France, 1 February 2017; Volume 97, p. 01056. [CrossRef]

43. Omar, M.F.; Ibrahim, F.A.; Omar, W.M.S.W. An assessment of the maintenance management effectiveness of public hospital building through key performance indicators. *Sains Humanika* **2016**, *1*, 1–7. [CrossRef]
44. Marzouk, M.; Hanafy, M. Modelling maintainability of healthcare facilities services systems using BIM and business intelligence. *J. Build. Eng.* **2022**, *46*, 103820. [CrossRef]
45. Lai, J.; Yuen, P.L. Performance evaluation for hospital facility management: Literature review and a research methodology. *J. Facil. Manag. Educ. Res.* **2019**, *3*, 38–43. [CrossRef]
46. Oppong, G.D.; Chan, A.P.C.; Chan, M.W.; Darko, A.; Adabre, M.A. Success Evaluation Index Model for Running Healthcare Projects in Hong Kong: A Delphi Approach. *Buildings* **2025**, *15*, 332. [CrossRef]
47. Hallowell, M.R.; Gambatese, J.A. Qualitative Research: Application of the Delphi Method to CEM Research. *J. Constr. Eng. Manag.* **2010**, *136*, 99–107. [CrossRef]
48. Ameyaw, E.E. Risk Allocation Model for Public-Private Partnership Water Supply Projects in Ghana. Ph.D. Thesis, The Hong Kong Polytechnic University, Hong Kong, China, 2015.
49. Sourani, A.; Sohail, M. The Delphi method: Review and use in construction management research. *Int. J. Constr. Educ. Res.* **2015**, *11*, 54–76. [CrossRef]
50. Ibrahim, C.K.C.I.; Costello, S.B.; Wilkinson, S. Development of a conceptual team integration performance index for alliance projects. *Constr. Manag. Econ.* **2013**, *31*, 1128–1143. [CrossRef]
51. Chan, A.P.C.; Yung, E.H.; Lam, P.T.; Tam, C.M.; Cheung, S.O. Application of Delphi method in selection of procurement systems for construction projects. *Constr. Manag. Econ.* **2001**, *19*, 699–718. [CrossRef]
52. Yun, S.; Choi, J.; De Oliveira, D.P.; Mulva, S.P. Development of performance metrics for phase-based capital project benchmarking. *Int. J. Proj. Manag.* **2016**, *34*, 389–402. [CrossRef]
53. Yeung, J.F.; Chan, A.P.C.; Chan, D.W. Developing a performance index for relationship-based construction projects in Australia: Delphi study. *J. Manag. Eng.* **2009**, *25*, 59–68. [CrossRef]
54. Niederberger, M.; Spranger, J. Delphi technique in health sciences: A map. *Front. Public Health* **2020**, *8*, 457. [CrossRef]
55. Yeung, J.F.; Chan, A.P.C.; Chan, D.W. Fuzzy set theory approach for measuring the performance of relationship-based construction projects in Australia. *J. Manag. Eng.* **2012**, *28*, 181–192. [CrossRef]
56. Ibrahim, C.K.I.; Costello, S.B.; Wilkinson, S. A fuzzy approach to developing scales for performance levels of alliance team integration assessment. *J. Constr. Eng. Manag.* **2015**, *141*, 04014094. [CrossRef]
57. Zadeh, L.A. Fuzzy sets. *Inf. Control.* **1965**, *8*, 338–353. [CrossRef]
58. Baloi, D.; Price, A.D. Modelling global risk factors affecting construction cost performance. *Int. J. Proj. Manag.* **2003**, *21*, 261–269. [CrossRef]
59. Singh, D.A.; Tiong, R.L. A fuzzy decision framework for contractor selection. *J. Constr. Eng. Manag.* **2005**, *131*, 62–70. [CrossRef]
60. Ng, S.T.; Luu, D.T.; Chen, S.E.; Lam, K.C. Fuzzy membership functions of procurement selection criteria. *Constr. Manag. Econ.* **2002**, *20*, 285–296. [CrossRef]
61. Chow, L.K.; Ng, S.T. A fuzzy gap analysis model for evaluating the performance of engineering consultants. *Autom. Constr.* **2007**, *16*, 425–435. [CrossRef]
62. Yeung, J.F.; Chan, A.P.C.; Chan, D.W. A computerized model for measuring and benchmarking the partnering performance of construction projects. *Autom. Constr.* **2009**, *18*, 1099–1113. [CrossRef]
63. Eye, A.V.; Schuster, C. *Regression Analysis for Social Sciences*; Academic Press: San Diego, CA, USA, 1998.
64. Xia, B.; Chan, A.P.; Yeung, J.F. Developing a fuzzy multicriteria decision-making model for selecting design-build operational variations. *J. Constr. Eng. Manag.* **2011**, *137*, 1176–1184. [CrossRef]
65. Bharathi-Devi, B.; Sarma, V.V.S. Estimation of fuzzy memberships from histograms. *Inf. Sci.* **1985**, *35*, 43–59. [CrossRef]
66. Yeung, J.F.Y.; Chan, D.W.M.; Chan, J.H.L.; Lok, K.L. Development of a Composite Project Performance Index for the New Engineering Contract (NECPPI) of construction projects in Hong Kong: A Delphi study. *Int. J. Constr. Manag.* **2023**, *23*, 2804–2817. [CrossRef]
67. Adabre, M.A.; Chan, A.P.; Darko, A.; Edwards, D.J.; Yang, Y.; Issahaque, S. No Stakeholder Is an Island in the Drive to This Transition: Circular Economy in the Built Environment. *Sustainability* **2024**, *16*, 6422. [CrossRef]
68. Adabre, M.A.; Chan, A.P.; Wuni, I.Y. Modeling Sustainable Housing for Sustainable Development in Cities and Communities: The Perspective of a Developing Economy. In *Circular Economy for Buildings and Infrastructure: Principles, Practices and Future Directions*; Springer International Publishing: Cham, Switzerland, 2024; pp. 97–115.
69. Muñoz, S.; Hosseini, M.R.; Crawford, R.H. Exploring the environmental assessment of circular economy in the construction industry: A scoping review. *Sustain. Prod. Consum.* **2023**, *42*, 196–210. [CrossRef]
70. Adabre, M.A.; Chan, A.P.; Darko, A.; Hosseini, M.R. Facilitating a transition to a circular economy in construction projects: Intermediate theoretical models based on the theory of planned behaviour. *Build. Res. Inf.* **2023**, *51*, 85–104. [CrossRef]
71. Han, S.; Jeong, Y.; Lee, K.; In, J. Environmental sustainability in health care: An empirical investigation of US hospitals. *Bus. Strategy Environ.* **2024**, *33*, 6045–6065. [CrossRef]

72. Love, P.E.D.; Ika, L.A. Making sense of hospital project (mis)performance: Over budget, late, time and time again—Why? And what can be done about it? *Engineering* **2021**, *12*, 183–201. [CrossRef]
73. Ammar, T.; Abdel-Monem, M.; El-Dash, K. Appropriate budget contingency determination for construction projects: State-of-the-art. *Alex. Eng. J.* **2023**, *78*, 88–103. [CrossRef]