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# BIM for Smart Hospital Management during COVID-19 Using MCDM

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**Abstract:** In context of the recent COVID-19 pandemic, smart hospitals' contributions to pre-medical, remote diagnosis, and social distancing has been further vetted. Smart hospital management evolves with new technology and knowledge management, which needs an evaluation system to prioritize its associated criteria and sub-criteria. The global effect of the COVID-19 pandemic further necessitates a comprehensive research of smart hospital management. This paper will utilize Analytical Hierarchy Process (AHP) within Multiple Criteria Decision Making (MCDM) to establish a smart hospital evaluation system with evaluation criteria and sub-criteria, which were then further prioritized and mapped to BIM-related alternatives to inform asset information management (AIM) practices. This context of this study included the expert opinions of six professionals in the smart hospital field and collected 113 responses from hospital-related personnel. The results indicated that functionalities connected to end users are critical, in particular IoT's Network Core Functionalities, AI's Deep Learning and CPS's Special Network Technologies. Furthermore, BIM's capability to contribute to the lifecycle management of assets can relate and contribute to the asset-intensive physical criteria of smart hospitals, in particular IoT, service technology innovations and their sub-criteria.

**Keywords:** smart hospital; building information modeling (BIM); Internet of Things (IoT); cyber physical system (CPS); service technology innovation



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## 1. Introduction

The smart hospital has been an essential part of the healthcare 4.0 trend [1]. In addition to being a key domain in the whole healthcare ecosystem, the smart hospital's evolution both drives and is affected by the healthcare economy and policy. Recent research has found that the healthcare domain has an active role in the societal transition to Society 5.0 [2]—the fifth science and technology-based plan for a human-centered society in which economic advancement is balanced with social problem resolution by a highly integrated system of physical and virtual spaces. Healthcare 4.0 is not only a specific up and coming trend within Industry 4.0; it is also a key component that Society 5.0 depends on [2–4].

Since early 2020, the COVID-19 pandemic's rapid spread globally has further impacted the healthcare industry, increasing the demand for hospitals' specific treatment facilities. Unfortunately, the traditional hospitals' physical building structures have imposed limitations such as difficulty to ensure or convert to negative pressure inpatient isolation wards, and up-to-date medical information systems to address the needs of special pandemic patients [5]. This extraordinary time of COVID-19 calls for the adoption of a more complete evaluation system for smart hospital management and building up the infrastructure.

Since the early 2000's, Building Information Modelling (BIM) has emerged to replace the traditional computer-aided design and drafting (CADD) for a wide variety of infrastructure design and development projects. In the context of Industry 4.0 trends that include many functions of smart manufacturing and smart asset management, the availability of new information management technology has influenced not only the methods and techniques, such as digital twin, but also the wholistic governance and management processes and strategies [6]. One of the major BIM uses towards the management of physical assets is its lifecycle contribution towards the asset information management system (AIMS), which contains geometric and non-geometric information derived from the information accumulated throughout the project lifecycle prior to the completion and commissioning of the physical built assets [7]. As the management of smart buildings from an organizational perspective is a key component of Industry 4.0 development, smart hospitals are among those institutions that can benefit from an evolved information system, as such systems would cover information pertaining to physical and digital assets, as well as information from clients (patients) or suppliers that would impact the management of operations of a smart hospital [8,9].

The recent outbreak of COVID-19 has created unforeseeable and unprecedented impacts on medical service behavior as well as all information management criteria with the smart hospital [10,11]—a major trigger for the next generation of BIM-based AIMS practices. Specifically, COVID-19's known observable impacts on the smart hospital asset management are manifold, including:

(a) Shifting demands of facilities within existing hospitals to cover the surge of COVID-19 patients' needs (e.g., conversion to negative pressure inpatient isolation wards, quarantine/isolation spaces, multifunctional use spaces, etc.);
(b) Increasing needs to provide space to patients, medical staff and equipment storage in response to increased forecasted COVID-19 patient flow and decrease in non-critical medical treatments; and
(c) Growing importance of real-time management and analysis of asset information, whose current criteria (broader categories) and sub-criteria (individual indicators) may fall short in satisfying the need for fast responses, the blurred boundary of room/space definition, and other not yet foreseeable challenges, which demands more systematic research.

In this context, it becomes imperative to reexamine the next evolution of Asset Information Management in the era of COVID-19, especially as the research on BIM-based AIMS for smart hospital criteria and sub-criteria in the era of COVID-19 are currently limited. Preliminary literature review indicates a gap in smart asset categorization that are beyond individual organizations or institutions, which oftentimes directly derive from empirical experience rather than structured research based on existing literatures and inter-organizational case studies [12]. Scientific quantitative research utilizing methods such as Multiple Criteria Decision Making (MCDM) has also largely focused on the individual, design and construction stages rather than the post-completion, asset-focused stages [13]. Moreover, with the predominant view and tendencies to establish predominant and consistent standards to minimize changes to AIMS, few literature sources exist linking BIM-based asset information management to black swan (unforeseeable) events, various types of real-time simulations and flexible response strategies, thus limiting the current capability for BIM-AIMS to contribute to the holistic smart hospital management in the era of COVID-19.

While international BIM-AIMS cases such as the World Health Organization (WHO), the Pan American Healthcare Organizations (PAHO) [14], the European Union Agency for Network and Information Security (ENISA) [15] and National Health Services Scotland (NHSScotland) [16] exist, there are gaps of industry practices and academic research. These research gaps have thus motivated this study to establish filtered, categorized and prioritized criteria for managing smart hospitals' assets via building information "management" by mapping asset management criteria between current BIM-AIMS competencies and needs relevant to COVID-19 in context of wholistic lifecycle assessment (LCA). This paper aims to answer the following research questions:

(a) How can smart hospital criteria and sub-criteria be synthesized, organized and prioritized in the contexts of the latest technological clusters available?

(b) Using BIM as a tool, how can smart hospitals shift their approaches to improve their current BIM-based asset management?

Through the MCDM (multiple criteria decision making) methodology, specifically Analytic Hierarchy Process (AHP), which has been proven effective on relevant yet narrower scope studies [17–20], the study would compile, filter, consolidate and prioritize a list of smart hospital criteria and sub-criteria, which are then translatable to BIM-AIMS categories and parameters upon review and advisory by BIM experts.

The paper is structured as follows. Following the introduction, Section 2 outlines each pillar of healthcare 4.0-enabled smart hospitals including the Internet of Things (IoT), cyber physical systems (CPS), artificial intelligence (AI), information management systems (IMS) and technology service innovation. Section 3 contains the research methodology and process in step-by-step detail, followed by results in Section 4, discussions in Section 4.4 and the conclusion in Section 5.

## 2. Theoretical Background and Criteria/Alternative Development

### *2.1. Smart Hospital Constructs in Context of Industry 4.0*

Since first mentioned at the Hanover Fair in 2011, the Fourth Industrial Revolution (also known as Industry 4.0) has gained significant momentum in driving the transformation of traditional manufacturing industries [21]. China has also "Made in China 2025" (MIC25), which strategically promotes the development and upgrade of the manufacturing industry from the labor-intensive factory into technology- and automation-driven factories. This national strategy, as part of the Thirteenth and Fourteenth five-year plans, is in fact demanding a transformation to "designed-in-china" and "innovated-in-china" and has been closely tied to the fundamental principles of Industry 4.0 [22]. By promoting direct machine to machine (M2M) communications, the maturing and commercialization of the Internet of Things (IoT) has allowed a higher degree of digital connection, visualization and automation of the machine components. Beyond manufacturing industries, similar transformations began for many other commercial sectors, organizations and government entities [6].

In context of the transformations within the healthcare industry, smart hospitals have also been optimizing their clinical processes, management systems and infrastructure. These changes or new components have been made possible by an underlay of digital network infrastructure of interconnected assets, which have increased service values and insights. The smart hospital's ability to achieve better patient care, experience and operational efficiency are within its three key layers: data, insight and access [12]. According to recent research and report of ENISA, a leading information management organization, a smart hospital is one that depends on optimized and automated processes, leveraging the ICT environment as a basis. The scope managed includes hospital staff, data, devices, core systems and core infrastructures—all of which are linkable through interconnected assets via the IoT, which could improve existing patient care procedures whilst introducing new capabilities [15]. Summarizing previous research, today's smart hospital management would involve complex spatial, technological and multidisciplinary considerations.

An examination of the available literatures has revealed synergies between five major constructs that are key to smart hospitals: the Internet of Things (IoT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI), management information systems (MIS) and technology service innovation [8,9,12,23]. Recently, literatures have further vetted that smart hospital management could benefit from the integration of contemporary technologies within those pillars of Industry 4.0. Kumar et al. [24] emphasized the integration of the IoT and AI to facilitate the management of smart hospitals, especially its patient-interfacing systems. Yang et al. [1] further argued that, in the era of "Healthcare 4.0", the combination of the IoT, CPS and AI could contribute to the development of comprehensive tools such as robotics to provide healthcare services. Alcácer & Cruz-Machado [25] has also highlighted that, in the context of the IoT, which is infinite in innovation and optimization possibilities, service technology innovations are often focused on one or multiple sub-criteria within the domains of the IoT, CPS, AI and MIS.

While the aforementioned individual in-depth research has focused on individual smart hospital constructs including the IoT, CPS, AI, MIS and technology service innovation, there is a current lack of comprehensive studies on how to relate and weigh all embodying criteria and sub-criteria under the smart hospital. This paper aims to fill this research gap by first gathering the criteria and sub-criteria within each construct from recent key literatures prior to using quantitative methods for prioritization and determining their relevance with BIM.

### 2.2. Internet of Things (IoT)

First coined by Ashton in 1998, the IoT has evolved from a futuristic concept of hypothetical internet infrastructure to the reality of coupling physical objects and virtual data via information extraction and communication through the internet [26]. The IoT is uses sensors, software and technology to enable a network of objects whose digital connection over the internet enables data exchange with each other and other connected systems. Due to its enablement by and reliance on the internet, the IoT is a paradigm shift that redefines the connectivity between objects, which, previously relying on physical proximity, is now less dependent upon proximity with and aid of the internet [24,27].

While increasing functionalities of the IoT are still being discovered, tested and implemented, the adoption of the IoT is not without limitations of procedures or boundaries. By further synthesizing the research of Patel et al. [27], the enabling factors of the IoT include: IoT core applications, which would include desktop software, mobile applications or other human interfaces to fulfil specific functions required; IoT Infrastructure, which would include the setup of internet-enabling equipment systems and interconnected protocols of radio-frequency identification (RFID); and IoT platform functionalities, which would include systematized cloud computing or local management platforms.

The IoT is not only one of the most important pillars of Industry 4.0; it is also an important foundation to individual industries' digital data transformation. One of the forerunners in adopting the IoT is the healthcare industry: according to recent surveys, healthcare is ranked No. 6 amongst the top 10 applications of the IoT in the industries, closely after manufacturing, transportation, energy, retail and cities, and exceeding the utilization of the IoT in supply chain, agriculture and buildings [28]. The increasing trend suggests that the "internet of medical things" (IoMT) is gaining traction. Focused research has also further investigated the Internet of Medical Things (IoMT)—the application of the Internet of Things in medical fields [10,29–32].

### 2.3. Cyber-Physical System (CPS)

CPS is a system characterized by its close interconnectivity of the physical components and software counterparts, whose balance depends on the user context and required functionalities [23,33]. CPS is congruent with the recent emerging trend of digital twinning and BIM-based applications [34,35]. While CPS's applications have been focused on virtual care and remote healthcare away from the hospital [36], CPS has been increasingly integrated into hospital management and operations [35,37].

By further synthesizing the research of [38], the enabling factors of CPS include: Special technologies, which would interface between cloud-based systems (with IoT capabilities) and mechatronic systems that allow the generation, transmission, distribution and consumption of information; functionalities, which create a feedback loop between the physical sensing of object domains and real spaces to produce actuation information; and service models, which would vary depending on the application ranging from transportation, medication, energy, chemical, engineering or finance, in the form of Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS).

### *2.4. Artificial Intelligence (AI)*

AI is machine-based intelligence. Opposite to natural intelligence (e.g., that of humans and other life forms), AI aims to produce "intelligent agents" using machine learning to recognize and analyze its environment, and subsequently performs actions that could most optimally achieve its prescribed goals [39–41]. Since the late 1990s, AI has gained importance in applications and trends that are smarter, more responsible and more scalable, according to industry research [42].

By further synthesizing the literatures, the enabling factors of AI are as follows. "Deep learning", which is the ability to utilize multiple layers and automate the processes beyond machine learning with representation learning within an artificial neural network [43]. "Expert system" is a computer system that is capable of simulating and closely replacing human experts' decision-making capabilities [44]. "Intelligent agent" is a device or machine-based protocol that is capable of perceiving and understanding its surroundings and subsequently takes the highest-and-best-use action to maximize its chances of achieving its objectives [45].

In the context of smart hospitals, AI has been increasingly used for analyzing medical data, especially big medical data [46,47]. AI can now assist medical professionals in most types of clinical decision-making, as non-human intelligence can now acquire knowledge about normal versus abnormal decisions by using the data generated by the health professionals and the patient through the feedbacks from machine and deep learning [48]. AI is capable of contributing to the evolvement of healthcare to become more "personalized, predictive, preventive and participatory", especially in biomedicine [49].

### *2.5. Management Information System (MIS)/Hospital Information System (HIS)*

MIS in an information system that is used to serve an organization with regard to its decision making, coordinating, controlling, analyzing and visualizing of information. In the context of smart hospital management, MIS is oftentimes referred to as HIS (hospital information system). Since it was first coined in late 1980s [50], MIS has emerged as the organizational mechanism to deal with interdepartmental information management.

The enabling factors of MIS include: "information receptors", which includes the output-end of the information towards medical staff and hospital operations' use for decision making; "information management", which includes the central core system where the information is stored and organized; and "information provider", which includes the input-end of the information receptor from patients, medical staff as well as the IoT sensors and is often enabled with communication and transmission technologies.

Recent research shows that MIS can help facilitate data analysis and decision making to improve the quality of medical care when resources are limited [51,52]. As technologies evolve, more uses of MIS are enabled for smart hospitals. Doctors and hospital operators could manage patient data comprehensively through one centralized platform [53–55]. In addition to a patient's medical records, real time clinical, treatment and care facilities can also be tallied and managed [56].

The adoption of MIS is not without barriers. Recent research shows that management support, self-efficacy and case-based approaches contribute to more effective adoption of MIS for hospitals, especially in context of developing countries [53,57].

### *2.6. Service Technology Innovation*

Service innovation is a service (either a product or a process) that is based on technological or systematic methods [58]. While such innovation is not always related to technology, as innovation could very well stem from non-technological dimensions, the innovation is specifically amplified when further infused with technology. Service technology innovation is deeply related to Industry 4.0 trends, especially when it comes to the adoption of the aforementioned tools such as the IoT, CPS and AI [25].

The enabling factors of service technology innovation include: Innovative service models, which refers to a different way to manage; innovative service interfaces, which includes non-conventional interfaces; and innovative service platforms, which includes different technologies that are often cloud-based, such as PaaS, SaaS and IaaS services infrastructures.

*2.7. Building Information Modelling and Building Information Management (BIM)*

Since the early 2000's, Building Information Modelling (BIM) has seen rapid acceptance and diffusion in the architecture, engineering and construction (AEC) industries. Sacks et al. [7] explicated BIM's precipitation throughout the lifecycle of a built environment to replace computer-aided drafting and design (CADD). While the paradigm shift brought forth by BIM has impacted the lifecycle of the industry, BIM itself has also gone through iterations of examination. Though still titled "Building Information Modelling", BIM is increasingly viewed as a service rather than another software solution or product offering [59].

Recent trends in standards suggest that there is a policy shift towards regulating BIM services such as model review, drawing generation, 3D coordination, as-built modelling and various analyses across project stages [7,60]. Moreover, one of BIM's key features is asset management, for which data is derived from the lifecycle information built up from planning, design and subsequent construction stages and is subject to minimum loss when BIM is employed.

Few international cases exist where standardized approaches are utilized for hospital employ smart hospital's asset management, including:

1. World Health Organization (WHO) and Pan American Health Organizations (PAHO): with an emphasis on "safety plus green equals smart", the WHO/PAHO have made recommendations beyond the physical buildings to include energy conservation, water conservation, indoor environmental quality, occupant survey and land use [14].
2. European Union Agency for Network and Information Security (ENISA): the guidelines contain both an overview of smart hospital assets, as well as organizational critical ranking [15]. The BIM-based organization can offer more information on smart hospital assets, which can help the doctor, nurse and related staff to easily understand the information of hospital and operation control.
3. Scotland's Health (NHSScotland): the most technical among the three, initially based on the building and asset information management foundation of PAS1192-2 and later conforming to Digital Britain, NHS's information management standard is based on Level 2 BIM that embodies classifications, digital plans of work, protocol and Construction Operations Building Information Exchange (COBie) as the main information exchange method [16].

In more recent trends, superseding BSI Kitemark for BIM Asset Management, which is based on the PAS 1192-3:2014, ISO 19650:3 of BSI standard with a focus on the progression of information requirements rather than on providing instructions on specific building or asset management criteria [61,62]. These standards are foundational to the ISO organizational or institutional smart hospital AIMS above and would also be examined for context purposes. Moreover, there has been a shift from geometrical (3D Models) and non-geometrical data (Data Models) in BIM as the project progresses through the lifecycle timeline [63]. While these institutional standards and guidelines have been formulated and implemented internationally, limited literatures exist with regard to how their asset criteria and prioritization were synthesized and how they specifically relate to the most important factors in smart hospital management. Nonetheless, these documents would serve as practical references and sources to harvest capital types, asset types and raw criteria which have been validated by the industry but are not limited to categorization and prioritization.

Relevant to this research and from the physical infrastructural asset perspective, ENISA's Smart Hospital publication synthesized eight types of assets within smart hospitals: interconnected clinical information systems, network medical devices, network equipment, remote care system, data repository, mobile client devices, identification systems and buildings [15]. These BIM-related sub-criteria can be mapped to previously established criteria in previous sections.

### *2.8. BIM and ICT-Related Alternatives*

While scholars have preliminarily identified the criteria of evaluation for smart hospitals, more specific innovative technologies are needed for smart hospitals management and medical processes, including ICT, AI, big data, robotic and cloud computing [25]. There is an urgent call for complete evaluation methods for decision-making. One of the important goals in the decision-making on evolving topics is to identify alternatives that can further improve the studied subject. This study utilizes the MCDM method to compute the priority of criteria, sub-criteria and optimal alternative objects for the goal of smart hospital management.

In addition to BIM's practical application and ability to integrate the IoT, CPS, AI and MIS, BIM's characteristics also befits that of a service technology innovation. Adding the discourse of BIM compensates for the ICT-related alternatives in the context of a rigorous decision-making structure. This research aims to investigate the MCDM methods' output of the evaluation results of smart hospitals and BIM's contribution in both enhancing its known criteria and sub-criteria, as well as potentially improving the available alternatives.

## **3. Methodology**

### *3.1. Research Process*

The research process is structured in three stages. First, a literature review was conducted, followed by the consolidation of smart hospital criteria, sub-criteria and alternatives, which formed Section 2. Subsequently, questionnaires containing the above were distributed to respondents, and collected responses were run through Expert Choice software to obtain scientific weighing of the results. Finally, alternatives optimum solutions were evaluated with expert choice. The overall research process is illustrated in Figure 1 below, while the rationale, detailed steps and analytical methods used are described in subsequent sections.

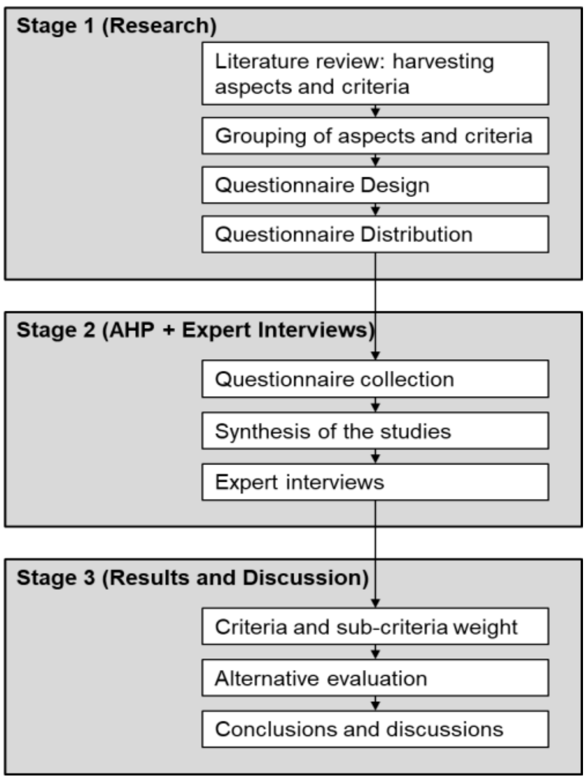


**Figure 1.** Research process.

### 3.2. Multiple Criteria Decision Making (MCDM)

To systematically arrange the criteria and their sub-criteria, and to weigh and prioritize them, a logical decision-making process shall be employed. This research will utilize Multiple Criteria Decision Making (MCDM). Also known as Multiple Criteria Decision Analysis (MCDA), MCDM is a method that focuses on evaluating multiple criteria and multiple targets in decision-making to resolve overlapping or conflicting decision-making problems. In the context of management and information systems, MCDM is often used to filter and prioritize a cluster of criteria gathered from industry fields, and the process could yield both industry demand and methodology contributions [13,64,65].

Tan et al. [13] further posited, through an extensive literature review and comparison, that MCDM is expected to play a significant role in the digital transformation process that the AEC industry is currently undergoing, and that MCDM could be effectively used in evaluating major BIM-related aspects such as sustainability, retrofit, supplier selection, safety and constructability. Furthermore, the research on smart hospital management needs to address multidisciplinary issues involving spatial and temporal considerations, hence further necessitating the need to utilize a comprehensive decision-making system. Previous research has validated MCDM/MCDA's use [66,67].

### 3.3. Analytical Hierarchical Process (AHP)

First formulated by Thomas L. Saaty in the early 1970s, Analytical Hierarchical Process continued to evolve and mature as a decision-making tool which has been proven suitable for determining priority when many assessment criteria coexist under uncertainty. AHP first establishes a hierarchy with two tiers to establish grouping relationships. Afterwards, through quantitative methods of surveying qualified respondents, the level of importance or relevance are determined through geometric-based calculations. AHP is able to encompass, consider and compare both tangible and intangible factors [17,68]. AHP has been deemed effective in simplifying complex decision problems when determining not only which factors are relevant, but also their level of importance in relation to other factors as a whole [69,70].

AHP is a decision-making method widely used by researchers and decision makers. AHP has three steps: modelling the problem as a hierarchy, evaluating the hierarchy and establishing priorities using a 9 to 1 to 9 scale [18,19,71,72]. The overall process of AHP is shown in Figure 2 below.

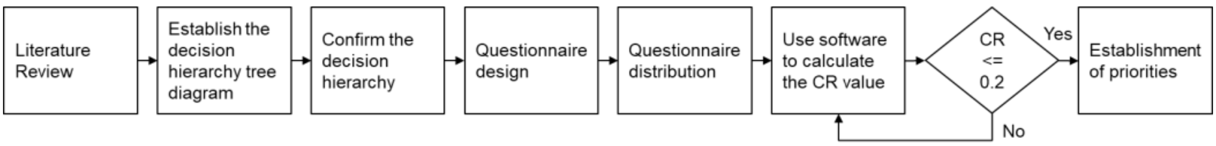


**Figure 2.** AHP workflow chart.

Within the BIM- and ICT-related MCDM framework, various methods compared by Tan et al. [13], AHP is most frequently employed and comparatively appropriate for consolidating, comparing, filtering and prioritizing multiple criteria. Haruna et al. [73] further promotes MCDM and AHP's strengths when it comes to BIM-based lifecycle assessments (LCA), especially towards sustainable building development and construction.

The AHP process can be described in detail in the following steps:

Step 1: Through literature review, formulate a two-tier hierarchical model which contains a balanced set of first-layer criteria and second-layer sub-criteria.

Step 2: Formulate and distribute questionnaires with regard to the criteria and sub-criteria from Step 1 to gather opinions about the importance level from participants. Referring to Table 1 below, the scales are as follows:

**Table 1.** AHP scales.

| Scale | Definition | Explanation |
|---|---|---|
| 1 | Of equal importance | The two activities contribute equally to the objective |
| 3 | Of moderate importance | Experience and judgement favor one activity over another |
| 5 | Of essential or strong importance | Experience and judgement strongly favor one activity over another |
| 7 | Of very strong importance | An activity is strongly favored and its dominance is demonstrated in practice |
| 9 | Of extreme importance | The evidence favoring tone activity over another is of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values between the two adjacent judgements | When compromise is needed between the explanations above |

Step 3: The questionnaires are distributed and collected, and the responses are tallied.

Step 4: The results are analyzed using the Expert Choice software which has been vetted by previous literature as being effective in priorities derivation, and whose limitations has no known adverse effects on this research [74]. The software goes through the following steps to generate the solution: problem modelling, pairwise comparison, judgement scale, priority derivation, consistency, aggregation and sensitivity analysis. For example, the comparison of the alternatives i and j is given by $p_i/p_j$, which multiplied by the priority vector $p$ results in: A $p = n\ p$ (where $p$ is the vector of the priorities, $n$ is the dimension of the matrix, and A is the comparison matrix).

The priority weight of the criteria and sub-criteria are calculated, and the final prioritization is obtained by multiplying the two. The consistency index (C.I.) and consistency ratio (C.R., which is C.I. divided by a random index, also known as R.I.) values are also calculated and verified. The hierarchy of C.I. and R.I. (C.I.H. and R.I.H.) are also validated. The consistency ratio hierarchy (C.R.H) is the value of C.I.H divided by R.I.H., and it is acceptable if C.R.H. < 0.1.

### *3.4. Questionnaire Design*

The questionnaire is designed in accordance with the five main criteria and their respective sub-criteria (3 each; 15 total). To minimize misunderstanding of the questions' meaning, the questionnaire is provided bilingually in English and respondents' native language (Traditional Chinese). After collecting basic information from interviewers, the main body of the questionnaire contains hierarchical comparison questions in pairwise, where the available answers are in a 9:1 to 1:9 scale in accordance with AHP methodologies [68–72]. Respondents are requested to check one box in each row to indicate his/her pairwise comparison judgement. Figure 3 below shows the sample matrix of the major criteria level where interviewees are required to check one box for each row.

| X Criteria | Pairwise Comparison Evaluation of Criteria (1 being the smallest and 9 being the largest in value) | | | | | | | | | | | | | | | | | Y Criteria |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Extremely | | Very Strong | | Strong | | Moderate | | Equal | | Moderate | | Strong | | Very Strong | | Extreme | |
| | 9:1 | 8:1 | 7:1 | 6:1 | 5:1 | 4:1 | 3:1 | 2:1 | 1:1 | 1:2 | 1:3 | 1:4 | 1:5 | 1:6 | 1:7 | 1:8 | 1:9 | |
| IoT | | | | | | | | | | | | | | | | | | CPS |
| IoT | | | | | | | | | | | | | | | | | | AI |
| IoT | | | | | | | | | | | | | | | | | | MIS |
| IoT | | | | | | | | | | | | | | | | | | Service Technology Innovation |
| CPS | | | | | | | | | | | | | | | | | | AI |
| CPS | | | | | | | | | | | | | | | | | | MIS |
| CPS | | | | | | | | | | | | | | | | | | Service Technology Innovation |
| AI | | | | | | | | | | | | | | | | | | MIS |
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**Figure 3.** Sample comparison evaluation matrix in the questionnaire.

### 3.5. Data Gathering and Sample

The research first seeks out respondents from healthcare fields in Taiwan. According to Health Care Index by Country 2021 [75], Taiwan is ranked the top country/region worldwide. Furthermore, as of mid-2021, [76], Taiwan not only has the lowest percentage of cases and deaths of COVID-19 to its population; it also has one of the highest track records in effectively quarantining, diagnosing and treating the cases. These results are testaments to the Taiwanese health system's ability to leverage its currently available resources in quick response to COVID-19 [11,66]. The medical field's experiences already gained from smart hospital's response to COVID-19, combined with factors such as ease of obtaining responses in a community where COVID-19 [77] is less rampant, justifies this research's focus on professionals in Taiwanese medical fields for questionnaire distribution as research targets.

Individuals from Taiwan's medical fields, including doctors, nurses, pharmacists and hospital management personnel were targeted for questionnaire distribution. A total of 470 hard copy survey forms were distributed to respondents, and 192 responses (42%) were collected within which 113 responses were valid (which equates to a 24% correct rate). The final collected sample size was 113 sampling (53% female, 60% over 45 years old and 33% working directly in the hospital). See Table 2 below for the detailed demographics description. Data were collected between May and October 2020 through a questionnaire in hard copy format.

**Table 2.** Demographics of sampling.

| Gender | Age | Education | Medical Working Fields |
|---|---|---|---|
| Male (53): 47%<br>Female (60): 53% | 20–34 yrs (27): 24%<br>35–44 yrs (20): 18%<br>45–54 yrs (26): 23%<br>55 and above (40): 35% | High school (12): 11%<br>University/College (62): 55%<br>Masters (33): 29%<br>PhD/Doctorial (6): 5% | Hospital (26): 23%<br>Medical Center (11): 10%<br>Educational (9): 8%<br>Informatics (5): 4%<br>Medical Labs (3): 3%<br>Pharmaceutical (10): 9%<br>Others (49): 43% |
| **Job Nature** | **Years of Experience** | **Nature of Organization** | **Organization Size** |
| Medica (39): 35%<br>Pharmaceutical (6): 5%<br>Administrative (13): 12%<br>Human Resources (4): 4%<br>Research (3): 3%<br>Sales (9): 8%<br>Education (5): 4%<br>Others (34): 30% | Under 1 yr (4): 4%<br>1–5 yrs (22): 19%<br>6–10 yrs (17): 15%<br>11–15 yrs (13):12%<br>16–21 yrs (8): 7%<br>22 yrs and above (49): 43% | Local Hospital (22): 19%<br>Local Teaching Hospital (4): 19%<br>Regional Teaching Hospital (4): 4%<br>Research Hospital (1): 1%<br>Regional Hospital (1): 1%<br>Quasi-Medical Center (1): 1%<br>Medical Center (11): 10%<br>Others (73): 65% | Under 50 (59): 52%<br>50–99 (9): 8%<br>100–199 (11): 10%<br>200–499 (5): 4%<br>500–999 (7): 6%<br>1000 and above (22): 19% |

### 3.6. BIM Expert Interviews

As the subject of COVID-19 evolves quickly, there are concerns for the efficiency and time span with the traditional Delphi method [78]. To further examine the criteria and sub-criteria and alternatives from an interdisciplinary perspective, focused expert interviews resembling the principle of Delphi were conducted. Such modified methods have recently been more widely used in interdisciplinary issues, including medical issues or AEC industry cases that require fast turnaround of expert opinions in the time of rapid technological or context changes [79,80].

For this study, the research team met with six experts, each with a minimum of 12 years of experience in BIM and knowledge of BIM management for healthcare through at least one past project, who were interviewed in depth to clarify the degree of relevance of BIM to criteria, sub-criteria and alternatives. The experts were also asked to advise on, from a BIM-centric rather than a smart-hospital-centric perspective, whether any improvements can be made to the best-fit criteria, sub-criteria and alternatives.

## 4. Results and Discussion

### *4.1. Smart Hospital Analytical Hierarchy Diagram*

As synthesized from review of recent literatures, Figure 4 below hierarchically shows the five major criteria of smart hospital management, their sub-criteria and four alternatives. Criteria C1 (IoT) and its sub-criteria (network core functionalities, network basic structure and network platform functionalities) were extracted from Section 2.2. Criteria C2 (CPS) and its sub-criteria (special network technologies, functionalities and service mode) were extracted from Section 2.3. Criteria C3 (AI) and its sub-criteria (deep learning, expertise system and intelligent agent) were extracted from Section 2.4. Criteria C4 (MIS) and its sub-criteria (information receiver, information manager and information provider) were extracted from Section 2.5. Lastly, criteria C5 (service technology innovation) and its sub-criteria (service innovation models, service innovation interfaces and functional platforms) were extracted from Section 2.6. Alternatives including medical process automation, medical robotics, precision medicine and portable sensors were summarized from Section 2.7. These criteria, sub-criteria and alternatives then served as the foundation for forming the questionnaire in accordance with the methods described in Sections 3.4 and 3.5.

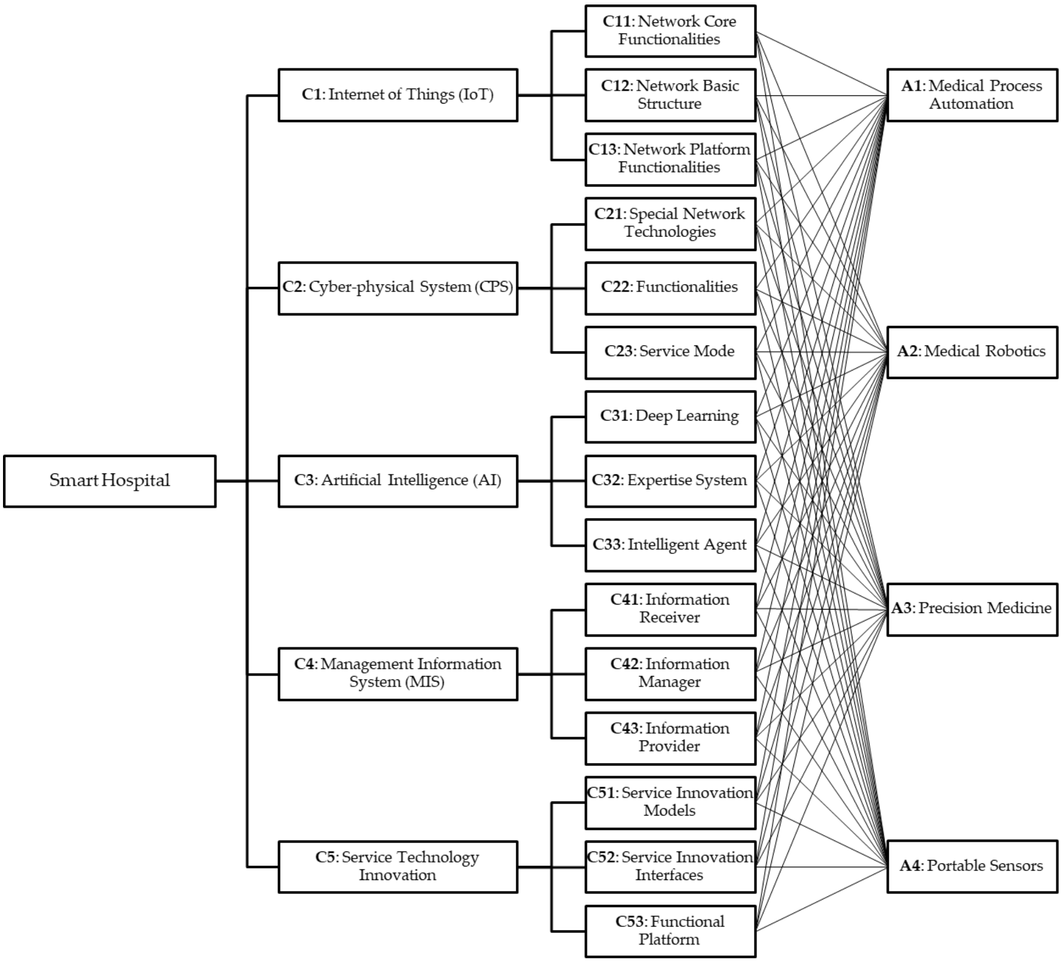


**Figure 4.** Smart hospital management criteria and sub-criteria.

### *4.2. Weighing of Healthcare 4.0-Driven Smart Hospital Criteria*

In accordance with the principles described in Section 3.3, Expert Choice was used to calculate the weighed priority and standard deviation (Std) of each criterion and sub-criterion. The final rank is a result of multiplying the sub-criteria's weight with the weight of the criteria it belongs to. The survey results are tabulated below in Table 3, with P being the weighed priority and Std being the standard deviation.

**Table 3.** Weighing of smart hospital criteria and sub-criteria.

| Criteria | Weight | Std | Sub-Criteria | Weight | Std | Final Ranks |
|---|---|---|---|---|---|---|
| C1 | 0.229 | 0.0923 | C11 | 0.435 | 0.1157 | 0.0997 |
| | | | C12 | 0.286 | 0.0386 | 0.0654 |
| | | | C13 | 0.279 | 0.1206 | 0.0640 |
| C2 | 0.193 | 0.0447 | C21 | 0.401 | 0.0932 | 0.0775 |
| | | | C22 | 0.301 | 0.0281 | 0.0581 |
| | | | C23 | 0.298 | 0.1052 | 0.0574 |
| C3 | 0.230 | 0.0273 | C31 | 0.406 | 0.0949 | 0.0934 |
| | | | C32 | 0.296 | 0.0193 | 0.0681 |
| | | | C33 | 0.298 | 0.0977 | 0.0684 |
| C4 | 0.173 | 0.0501 | C41 | 0.385 | 0.0946 | 0.0659 |
| | | | C42 | 0.295 | 0.0341 | 0.0554 |
| | | | C43 | 0.319 | 0.1154 | 0.0517 |
| C5 | 0.175 | 0.0620 | C51 | 0.385 | 0.0946 | 0.0674 |
| | | | C52 | 0.295 | 0.0341 | 0.0517 |
| | | | C53 | 0.319 | 0.1154 | 0.0559 |

As C.I. = 0.027, C.R. = 0.046 and C.R.H. = 0.0205, the result's consistency passes the requirement that C.R.H. < 0.1 and is acceptable for further interpretation.

In terms of the main criteria, it can be concluded from the table above that C3 (Artificial Intelligence) has the highest (weight, 0.23; Std, 0.0273), followed by C1 (the Internet of Things—IoT) (weight, 0.229; Std, 0.0923). The respondents' collective opinion indicates that C2 (Cyber-physical System—CPS) is of less importance (weight, 0.193; Std, 0.0447). Of all the main criteria, C5 (Service Technology Innovation) (weight, 0.175; Std, 0.062) and C4 (Management Information System—MIS) (weight, 0.173; Std, 0.0501) are of the least priority, with the second and third highest standard deviation figures, thus implying high level of disagreement and necessity to review the sub-criteria priorities.

When further examining the sub-criteria, network care functionalities and deep learning functionalities are more important for smart hospitals. It also becomes evident that, even though some main criteria are of lesser priorities, service innovation models and functional platform are both highly relevant to smart hospitals. CPS functionalities and the MIS information receiver are also perceived as more critical than the providers, managers and interconnecting systems.

Overall, there appears to be a strong preference for the functionalities over platform or network capabilities. Although respondents are from diverse fields within healthcare fields, they have assigned higher importance to the end-user function-driven elements over systems, operation and manager components.

### *4.3. Evaluation of Alternatives with BIM Expert Input*

In addition to calculating the weight, standard deviation, C.I., C.R. and C.R.H. values in the previous section, Expert Choice was also used to calculate the weight of the four alternatives. The priorities of the alternatives are as follows per Table 4:

**Table 4.** Weighing of alternatives within IoT.

| | Weight | Std |
|---|---|---|
| A1 (Medical Process Automation) | 0.326 | 0.1152 |
| A2 (Medical Robotics) | 0.209 | 0.0248 |
| A3 (Precision Medicine) | 0.277 | 0.0588 |
| A4 (Portable Sensors) | 0.188 | 0.0701 |

In sum, the four alternatives have all achieved a weight of over 0.18, which signifies the validity of their importance to smart hospitals. It can be synthesized that A1 (medical process automation) leads, followed by A3 (precision medicine), with a significant margin over A2 (medical robotics) and A4 (portable sensors). Specifically, the importance of medical process automation directly relates to IoT and AI technologies, both of which have been deemed critical through the analysis of AHP results.

In terms of integration with BIM, the four alternatives have varying degrees of relations and dependencies with BIM. In combination with previous literature, experts' opinions from the Modified Delphi Method rank the alternatives' relationship to BIM in the following order (strongest to weakest): A4 (portable sensors), A2 (medical robotics), A1 (medical process automation) and A3 (precision medicine). Portable sensors and medical robotics have more relevance to BIM due to their ability to integrate with the IoT and ICT as consistent with current research [10,29]. However, without highlighting a specific systematic relationship to BIM implementation within these alternatives, the resulting scores are much weaker compared to those of medical process automation and precision medicine, towards which BIM's relevance is limited.

The BIM expert interviews, in addition to reviewing the weight of these alternatives, also aim to buttress the alternatives' limitations by providing novel use cases that have not yet been incorporated in existing literatures. Firstly, in terms of medical robotics, experts suggested that the underlying information infrastructure of medical robotics can be supported by the digital twin of BIM-enabled smart hospitals, in particular through a common data environment (CDE) linking to the CPS to serve as a single source of truth.

In terms of portable sensors, experts confirmed a strong link to the IoT and the IoMT extensions of BIM whose rapid expansion of applications includes mapping of such sensors to specific areas and systems. BIM experts also suggested not to overlook a balanced approach between fixed sensors which can target all-time high-risk spaces such as negative pressure wards and temperature detection gauges, whilst leveraging the flexibility of portable sensors, which can fulfil multipurpose scenarios with shifting demands in the 24/7 hospital environment. It was noted by the majority of experts that portable sensors would be measurably useful in temporary spaces such as quarantine areas and expanded waiting areas due to social distancing.

### *4.4. Discussion*

This research aims to establish, organize and prioritize the criteria and sub-criteria of smart hospital management in context of the COVID-19 pandemic. From the research, it is found that the importance of CPS and the IoT both lead with big margins compared to the other main criteria, with a very narrow difference between their perceived relevance to smart hospital management. While it may seem that Service Innovation is of less importance, its sub-criteria "service innovation models" and "functional platforms" are still deemed essential. Similarly, CPS functionalities and MIS information receiver weigh more than other components of the system they are connected to. The findings are congruent with prior research that smart hospitals can use better integration of these technologies to achieve better management [8,9,12].

The overall preference for the functionalities of each criteria over their platform or network capabilities as observed in Section 4.2 could be indicative that most respondents value end-user, function-driven elements over systems, operations and manager components. The responses may be subject to further interpretation, such as respondents' knowledge of the most advanced platform, network and manager functionalities that are currently available. As some of the most recent literatures have indicated, some of the criteria such as AI and MIS (and even the IoT/IoMT, which is familiar to most) are still under rapid technological development [30,46,47,55]. The maturity and wider implementation of individual functionalities over connective network or platform aspects may have an impact on survey responses.

In terms of alternatives, the BIM-infused alternatives included are ranked less effective than the medical-procedure-based alternatives. However, it should not be interpreted that BIM is irrelevant or not as useful when it comes to smart hospital management. First, as all respondents come from medical fields, they are more well versed in precision medicine and medical process automation, but not all respondents could make automatic or intuitive connections to backbone technologies of medical robotics and portable sensors, which are supported by BIM and ICT. Second, the result also echoes previous research's claim that the wholistic and comprehensive application of BIM would be more conducive and well-received compared to standalone functions [23,25]. Lastly, in context of the ongoing COVID-19 pandemic, the urgent focus has been on direct medical interventions rather than longer term physical elements such as medical robotics and portable sensors.

An important step after the MCDM AHP process is to validate and enhance the quantitative results with expert views. With the aid of BIM experts' perspectives, it was found that the current lack of BIM implementation in these alternatives, especially medical robotics and portable sensors which have potentials of leveraging already maturing technologies from criteria such as the IoT and CPS, with the ability to link to MIS (HIS). Ultimately, the expert opinions support BIM's ability to further strengthen the relationship between these alternatives and smart hospital infrastructure, echoing recent findings by Isikdag [59].

## 5. Conclusions

### *5.1. Answers to Research Questions*

Smart hospital management, an important domain in the context of Industry 4.0 and Society 5.0, has gradually involved more technological and innovative considerations. While currently challenged by the COVID-19 pandemic, the adversity and challenges brought forth by the need and opportunity to comprehensively review the criteria and alternatives. The research has addressed the questions it posed in Section 1:

(a) To synthesize, organize and prioritize smart hospital criteria and sub-criteria in contexts of the latest technological clusters available, Analytical Hierarchy Process (AHP) within Multiple Criteria Decision Making (MCDM) has been used to scientifically and systematically distill, categorize and prioritize the criteria, sub-criteria and alternatives.

(b) Using BIM as a tool, smart hospitals shift their approaches to improve their current BIM-based asset management by leveraging BIM experts' feedback towards alternatives established through AHP. The feedback emphasized the importance of spatial applications such as: (i) digital twin adoption which blends CPS, CDE and medical robotics; (ii) system- or area-specific sensors with a balance between fixed and movable; and (iii) optimizing the use of AI towards non-geometric data (LOD-I) within BIM.

### *5.2. Theoretical Contributions*

As an overall comprehensive framework, the resulting hierarchy provides a valid foundation for future location-specific and discipline-specific queries into the level of importance for a particular sub-set of smart hospital. The research adds to Saaty's prominent MCDM method [17,68]—AHP—to prioritize and inform the criteria and sub-criteria, as well as Tan et al. (2021)'s research of BIM using MCDM methods. This research utilizes the MCDM method for the evaluation of the domain, criteria and target alternatives which were synthesized from literature review and theoretical explorations. Thereafter, through Experts Choice the weights for priority of goals were calculated. The research also involves Experts Choice method to merge latest trends systematically into the theories. Lastly, the research validates the systematic potential of BIM approach for designing an optimized smart hospital system in response to the current COVID-19 pandemic.

### *5.3. Practical Implications*

From the results of this research, hospitals could choose to dispense their limited resources on criteria and alternatives with higher priorities, especially when funds and healthcare workforce are further limited in the event of an unforeseeable pandemic. For example, smart hospitals may take into consideration that the functional aspects were deemed more critical than background systems and managers and focus on end users' functional requirements when improving the smart hospital infrastructure.

The ability for hospitals to distribute their limited resources through logical and hierarchical decision making, especially on its physical spaces and assets, has followed up and vetted Tan et al.'s conclusion of synergies between MCDM and BIM [13]. The results also shed light on current practices of already established standards [14–16]—when future decisions are made with regard to BIM-infused smart hospital management, the owners and managers may consider focusing on attainable implementations that are within the prioritized list.

### *5.4. Limitations and Future Research*

This research is focused on smart hospitals and has limitations with regards to the larger smart healthcare ecosystem that are not within the physical boundaries of smart hospitals. Trends such as telemedicine, technology-infused preventative care, and big data-focused healthcare information aggregation and analysis could be further explored. New technologies have the potential of removing the barrier of receiving professional care, and the role of the criteria and sub-criteria within this research, as well as other up-and-coming technological advancements, could be further investigated to benefit the prioritization of smart hospital resources.

As the recent COVID-19 pandemic is still ongoing, this research has pointed out the importance of BIM- and IoT-related smart hospital management at the peak of the outbreak. More investigations could be focused on the balance between treatment activities, technology-enabled equipment and the management of physical assets or environments. Further research would be necessary to address the rapid changes, especially going from peak-COVID, post-COVID to the next unknown pandemic.

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