A hybrid assessment framework for human-centred sustainable smart campus: A case study on COVID-19 impact

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Abstract
The continuous development of modern information and communication technologies is driving the smart revolution in the global education system. The outbreak of the COVID-19 pandemic has recently posed unprecedented challenges to educational institutes. The education informatisation technologies are playing a vital role to ensure the continuity and enhance the performance of education during the pandemic, which accelerates the integration of cutting-edge technologies and thus the overall development of the smart campus. Alongside the technological advancement, the existing studies indicate that the success of smart campus development mainly depends on three key dimensions: technology capability, sustainability, and student health and well-being. However, the state-of-the-art assessment on smart campus are mostly unilaterally dependent but lack a balanced evaluation of the three dimensions. To bridge this gap, this paper proposes a hybrid assessment framework that integrates all three key aspects, aiming to provide a multi-dimensional view of campus smartness for human-centred sustainable development. The smart campus assessment index resulting from the proposed framework is constructed under a limiting factor formulation to jointly model the individual contributions from the three dimensions as well as their trade-off relationship. The contribution from each dimension is the weighted normalised sum of a set of precisely selected indicators. A case study is also conducted on the historical data of a US university to investigate the effectiveness of the proposed framework and the assessment index in response to the COVID-19 pandemic, which also demonstrates the rationality of the hybrid framework for smart campus assessment.

1 | INTRODUCTION

Along with the continuous development of modern information and communication technologies (ICT), the global education system is experiencing its smart revolution. The world is recently paying increasing attention to smart education in promoting economic and social development. Many regions have seized the opportunity of a new round of education reform to enhance the future international competitiveness of their talents. The U.S. Department of Education is committed to leveraging the power of technology to rethink education and has been making efforts on National Education Technology Plan’s five goals including learning, assessment, teaching, infrastructure, and productivity [1]. Japan department formulated the ‘i-Japan Strategy 2015’, which pointed out the need to deepen the ICT application in education based on networking and cultivate talents capable of innovative technologies for the future needs of smart cities [2]. Hong Kong Education Bureau launched the newest Fourth Strategy on ICT in Education, which is formulated to unleash the learning power of all students through realising the potential of ICT in enhancing interactive learning and teaching experiences [3]. In Australia, Digital Education Revolution was funded by the government aiming at increasing the ICT proficiency of students and teachers throughout all Australian schools, as well as nourishing the use of novel technologies in teaching and learning development projects and research [4]. In 2020, Australia’s New South Wales government has allocated a $2.1 billion Digital Restart Fund to boost regional and remote education in the state [5].

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Since the outbreak of the COVID-19 pandemic, educational institutes have ushered in unprecedented challenges. The smart campus plays a vital role to ensure continuity and enhance the performance of education. Through smart technologies, online education effectively breaks the distance between time and space and improves the development of education informatisation.

The advancement in technology serves as the key driver of this smart campus evolution. Numerous pieces of literature related to smart campus have developed or applied cutting-edge technologies that can be categorised into 5 domains: (1) data computing and storage technologies, for example, clouding computing and edge computing [6, 7]; (2) Internet of Things technologies, for example, smart sensors and new communication protocols [8–10]; (3) intelligent technologies, for example, artificial intelligence and computation intelligence [11]; (4) immersive technologies, for example, augmented reality and virtual reality [12–14]; and (5) mobile technologies, for example, mobile phones and tablets [13, 15]. However, the existing research broadly focuses on a range of innovative technologies but lacks measurement solutions to evaluate the performance of the emerging technologies on smart campus. This paper will strive to make a comprehensive assessment of the smart campus.

Sustainability is generally referring to the development that meets the needs of the current generation without compromising the ability of future generations to meet their needs, which is further explained as the balance of economy, environment, and society in global development. The Sustainable Development Goals (SDGs) established by United Nations (UN) not only identify the objectives but also pave the roadmap towards sustainability [16]. However, the COVID-19 pandemic presents an enormous challenge for reaching the SDGs. During the outbreak of the pandemic, UN Educational, Scientific, and Cultural Organisation (UNESCO) has been using ICT to support distance education to ensure the continuity of education to promote educational equity through technological means to achieve the goals of Education for Sustainable Development [17]. The increasingly important role of novel technologies in the education system reflects that smartness is the power to sustainable development and resilience. A smart campus is envisioned as a principal–agent for addressing the sustainability challenges that the education system is facing. It enables technologies to contribute to a sustainable society in terms of education, research, and collaboration with society and campus development. As a mini version of a city, a smart campus can extrapolate its sustainability achievements to smart cities, showing the importance to achieve and assess measurable sustainable outcomes.

Our previous work highlighted that as a socialised educational environment, the development of a smart campus should adhere to the human-centred principle, which is to put the needs and interests of stakeholders as the first priority [18–20]. To assess the adherence to the human-centred principle, health and well-being (H&W) of students in smart campus would be appropriate metrics. Generally speaking, health does not merely refer to the absence of disease or infirmity. The World Health Organization has officially defined health as a state of complete well-being in three aspects: physical, mental, and social [21]. The enjoyment of the highest attainable standard of H&W is one of the fundamental rights of every human being including students in schools. While sustainability can provide a macro-level measurement of the social aspects, H&W focuses more on the micro-level stakeholders' social satisfaction in campus lives. The incorporation of sustainability and H&W can reflect the true human-centred sustainability of a smart campus. Therefore, ensuring and promoting student H&W is essential for expanding social factors from macro to micro level for students' feeling to be truly involved.

As mentioned above, the success of smart campus development depends on three key factors: technology capability, sustainability, and H&W, which is graphically presented in Figure 1. However, the state-of-the-art measurement index for education institutes is mostly unilaterally dependent, but there is a lack of a balanced evaluation for assessment. This paper proposes a hybrid assessment framework that covers all three key aspects to provide a multi-dimensional view of campus smartness, which could potentially contribute to the human-centred sustainable development of the future smart campus. Based on the proposed framework, this paper also presents a case study to demonstrate the rationality of the hybrid framework by observing the variation of the assessment index and its components of a US university in response to the COVID-19 pandemic. The main contributions of the work are summarised as follows:

1. The new assessment framework that integrates technologies, sustainability, and H&W dimensions can provide a comprehensive view of the smart revolution. It can not only measure campus smartness from individual dimensions but also describe the relationships and dependencies among these dimensions.
2. The resulting index from the proposed assessment framework provides a multi-dimensional reference that can facilitate decision-makers to develop more balanced solutions for smart campus planning and a roadmap, to achieve a human-centred sustainable smart campus.
3. As a part of smart cities, the smart campus assessment framework and experience developed in this paper can also provide a technology-sustainability-wellbeing template that informs the development of the smart cities as a whole as well as the sub-systems undergoing a smart revolution, such as energy systems, health systems, transportation systems, financial systems, etc.

The rest of the paper is organised as follows: Section II reviews the state-of-the-art assessment methods and indices for smart campus; Section III elaborates on the proposed hybrid assessment framework for smart campus; Section IV presents the potential applications that the proposed assessment framework and index can fit in; Section V presents a case study to demonstrate the effectiveness of the proposed assessment framework and index, and Section VI concludes the paper.
2 | RELATED WORKS

This paper proposes to assess a smart campus through three dimensions: technology, sustainability, and well-being. There are existing metrics or indices for each dimension reported in different countries and systems. This section reviews the existing smart campus indices to provide the basis and reference for developing the new assessment framework.

2.1 | Assessment of technology dimension

The realisation of a smart campus relies on a diverse stack of technology capabilities. Focussing on creating an interconnected smart learning and living space on campus, various cutting-edge technologies, such as distributed computing, IoT, mixed reality, and AI, are increasingly deployed. For example, cloud computing as an advanced distributed computation technique enables learning activities in an unstructured environment while meeting information security requirements, which has brought a whole host of benefits for students through e-learning and remote learning. IoT provides an effective enhancement in campus monitoring and event tracking, which allows automation of campus operation. Augmented Reality allows the real world to be vividly augmented with virtual content, which helps create more interactive classroom environments enabling students to learn faster and in enhancing their creativity and imagination. Artificial Intelligence injects intelligence and autonomy attributes into various campus applications such as learning material customisation, personnel recognition, tracking, and future condition prediction. All these technologies can more or less influence the effectiveness and efficiency of campus education and operation, but their deployment levels and the effects could be very different across schools. In this situation, appropriate metrics to measure the technological advances towards campus smartness would be necessary as a reference to guide smart campus development.

Previous studies proposed various measurements or indices for evaluating the performance of technologies in the

FIGURE 1 Key factors related to smart campus development
context of smart campuses. In Ref. [22], technology satisfaction was investigated through a questionnaire approach to evaluate smart technologies' influences on learning. Incidence matrices on 5 fields (i.e. people and living, economy, energy, environment, and mobility) are used in Ref. [23, 24] to evaluate the technological advancement and plan the strategy for smart campus development. In Ref. [25], a global set of indicators involving economic, energy environmental, and social aspects was defined to conduct a complete and holistic assessment of state-of-the-art technologies used in smart campuses. In Ref. [26], relevant Key Performance Indicators covering the needed fields were extracted to support the main business process of a university campus, such as smart buildings, pollution, waste management, water resource management, and health care provision, thereby establishing a mechanism that allows monitoring the smartness of a university campus in general.

2.2 Assessment of sustainability dimension

Sustainability is an excellent term to measure the effectiveness of technology advancement, owing to its balancing view on the economy, environment, and society. Notably, the SDGs have been widely recognised in most countries and have been adopted as the best guidelines to date to convey what a sustainable world should look like for long-term aspirations. This requires the development of a long-term mechanism for evaluating SDG performance. The 17 SDGs cover the three major groups of Environment, Society, and Economy, which represent the three pillars of sustainability and aim to guarantee the planet's integrity and improve the quality of life. Recently, many educational institutes have begun to align their strategic priorities to the 17 SDGs, which foster the establishment of globally recognised metrics to measure campus sustainability towards SDGs. For instance, the Times Higher Education Impact Rankings are global performance tables that evaluate university performance against the SDGs through research, teaching, outreach, and stewardship efforts. The Impact Rankings cover all the SDGs and provide open and transparent guidance that allows direct engagement of universities and higher education institutions through metric calculation.

For campus sustainability assessment, many other indices have been developed since 2001 that are comparable and easily measurable. For example, Campus Sustainability Selected Indicators Snapshot and Guide [27] provided a quick overview of campus operations and ecological influences. GREENSHIP [28] is a building certification intended to improve building design and construction, covering site development, energy efficiency and conservation, water conservation, material resources, and cycle, indoor health and comfort, and building environment management. Auditing Instrument for Sustainability in Higher Education (AISHE) [29] was established as a classic index for higher education institutions inspired by a tool for general quality management in higher education. Assessing Responsibility in Sustainable Education based on ISO 26000 [30] was further established to extend the sustainability assessment to faculty or a service department. GreenMetric [31] and Times Higher Education Impact Rankings [32] are two important metrics for the global ranking of universities' sustainable behaviour. GreenMetric aims to assess the policies and activities within the green campus to promote sustainable cultures in universities, whereas the Impact Rankings assesses universities' impacts on the UN's SDGs. The Sustainability, Training, Assessment, and Rating System [33] is a transparent, self-reporting framework to assess the sustainability performances of campuses in various fields of operation, education, research, and outreach. This framework opens specifically for higher education institutions, encompassing all the long-term SDGs that have been achieved and the entry points for taking the first steps towards sustainability. In Ref. [34], an evaluation system was developed to assess and compare the sustainability performance of universities in China. A generalised guidance framework was proposed in Ref. [35] for creating sustainability assessment models and deciding on effective assessment indicators.

2.3 Assessment of health & well-being dimension

Numerous studies show that increased impairment of students' health and well-being can negatively impact learning achievement [36]. However, most existing research and policies have focused on relationships between the physical campus and humans' physical health rather than mental health and complete well-being. One of the goals of a smart campus should be to provide a smart community environment that maximises the level of health and well-being of students in their educational experience and school lives, which adheres to the human-centred principle of smartness.

In the literature, many indices and methods have been developed and used in different countries to assess student health and well-being. For example, a focus group discussion based on a School Well-being Model [37] was employed in Ref. [38] to assess the well-being of students from secondary schools. Two cross-sectional surveys, one on students' general health survey and the other one on students' satisfaction with teaching and learning experience, were conducted [39] to investigate the health and well-being of university students in the United Kingdom. The Australian Unity Personal Well-being Index [40] and the Growth and Empowerment Measure [41] were combined in Ref. [42] to measure the well-being of first-year undergraduate students. The web-based survey named University Student Health and Well-being Study was established in Ref. [43] as a foundational tool to assess university students' health in Australia, aiming to inform effective programming, policy, and initiatives in higher education institutions.

Well-being can be categorised as subjective or objective well-being by its definition. Precisely, the well-being dimension highlighted in this paper mainly refers to subjective well-being (SWB) since the measurement of objective well-being has been included in the sustainability dimension as in SDG3 [16]. The empirical links between SDGs and SWB have been discovered
in Ref. [44], indicating that SDGs can be either positively or negatively correlated to SWB. From this point of view, short-term sustainable development needs certain trade-offs and each SDG has variance in its contribution to SWB. Subjective well-being emphasises the happiness and satisfaction that people experience and evaluate their lives, which is based on individuals’ self-evaluations of their own life. Therefore, the measurement to capture SWB levels is generally different from objective well-being indicators with observable outcomes. In the 20th century, gross domestic product (GDP) has been utilised as a major indicator of well-being focussing on economic growth. Recent studies have endeavoured to seek alternative indicators to GDP for SWB measurement based on the purpose of simultaneously achieving sustainable development and advancing SWB. In Ref. [45], Sustainable Wellbeing Index was investigated in connection with the SDGs for the measurement purpose. In Ref. [46], a model that includes various indicators to create a more meaningful and useful measurement of sustainable well-being was identified. A College Student SWB Questionnaire was designed in Ref. [47] to assess the mental health of college students in the United States, through a domain-specific measure that examines the associations between Big Five personality and college student SWB.

2.4 | Research gap in smart campus assessment

As shown in the literature, various measurement indices have been developed for smart campus assessment in technology, sustainability, and H&W dimensions, which support the inclusion of these three dimensions in smart campus assessment and provides extensive technical references for each dimension. However, these existing indices can hardly show the synergies among the three dimensions as they are designed isolately, and lack a comprehensive view of the smart campus condition. In a sustainable human-centred smart campus, technology evolvement would be a crucial driver of the variations in sustainability and H&W, whereas the observation of the changes in sustainability and H&W would also provide traceable evidence to guide the balanced planning and development of a smart campus. To reflect such a multi-dimensional relationship requires the appropriate integration of three dimensions in a single metric tool for a more comprehensive assessment of campus smartness and its impacts.

3 | HYBRID FRAMEWORK FOR SMART CAMPUS ASSESSMENT

This section elaborates on the proposed hybrid assessment framework for evaluating sustainable human-centred smart campus, which includes the overall framework and the quantitative methodologies.

3.1 | Hybrid framework

Technology, sustainability, and H&W are three key dimensions involved in smart campus development. The hybrid framework proposed in this paper aims to comprehensively incorporate all these three dimensions and appropriately integrate the indicators from the three dimensions into a single index.

For a start, the index can be constructed using the following mathematical formula:

$$ HI = f(T, S, H) \quad (1) $$

where Hybrid Index (HI) represents the hybrid index. T, S, and H are the contributions in technology, sustainability, and H&W dimensions, respectively. f is the function that integrates the three elements into the hybrid index.

The design of function f is critical to the rationality of the final index for smart campus evaluation. Considering that the three elements are all essential in the construction of a smart campus, the absence of any element should lead to a zero value for the overall index. In this situation, a simple linear combination of them would not be suitable. Another proposal of f would be the multiplication of the elements to reflect their essences. However, this will lead to infinite value in the extreme case. Such a phenomenon is not allowable considering the fact that the pursuit in one dimension may limit the development in another dimension. For example, the deployment of new technologies in schools can generate privacy and security impacts related to sustainability and stakeholder welfare, and the technological boundary depends on not only the way of using the technology but also the awareness from stakeholders as well as the regulatory constraints on environmental sustainability. With the above considerations, we propose a limiting factor framework to integrate the three elements. The hybrid index is thus defined as follows:

$$ HI = L_{\text{max}} \times T \times S \times H \quad (2) $$

where $L_{\text{max}}$ is the maximum achievable index value when the contributions from all dimensions are at their maximum values. T, and are the normalised values of the contributions of each dimension to the hybrid index. In the above formulation, $L_{\text{max}}$ is a user-defined value that can be nominated in any relevant unit. The simplest way would be a unitless maximum on a 0 to 10 or 0 to 100 scale. The index approaches $L_{\text{max}}$ as all element values approach to 1. Moreover, T, S, and H serve as the limiting factors on $L_{\text{max}}$ which fosters the balanced development in all three dimensions instead of skewing to a one or two of them. For example, if T is very large, its term in (2) will approach to 1. But in the meantime if S is small, the overall value of HI will be reduced and the efforts in technology dimensions will be impaired.

The normalised contributions from each dimension is calculated as follows:
where $X$ represents either $T$, $S$, or $H$; $D_{X,i}$ denotes the $i$th indicator in $T$, $S$, or $H$ dimension; and $\tilde{X}_{i}$ is the weight of $D_{X,i}$. $D_{X,i,max}$ and $D_{X,i,min}$ are the maximum and minimum values of $D_{X,i}$. It should be noted that the increase in individual indicators can positively or negatively affect the contribution from its corresponding dimension. For indicators with negative impact, the reciprocal of the original indicator value is used in (3) and (4) to make a unified quantification. Weighting factors are applied in this framework to leverage the impact of individual indicators on the overall contributions of each dimension to the hybrid index. The weighting factors can be assigned different values for individual indicators based on the circumstances and strategies of specific educational institutions and the weight factors can also be adjusted over time based on the ambient variations, but this paper adopts equal weighting factors as follows in order to make a unified comparison

$$\tilde{X} = \sum_{i=1}^{N_X} \tilde{w}_{X,i} \tilde{D}_{X,i}$$

$$\text{where } \tilde{D}_{X,i} = \frac{D_{X,i} - D_{X,i,min}}{D_{X,i,max} - D_{X,i,min}}$$

The min-max method in (4) can normalise the variables to the range [0, 1]. Since the existing indices in all dimensions as reviewed in Section II do not show the possibility of infinity in their definitions, the min-max method would be sufficient to normalise the existing indices and coordinate their different scales. By theory, the proposed framework is open to incorporating the existing metrics currently used in different countries.

### 3.2 | Suggested indicators in technology dimension

A smart campus resembles a miniature of a smart city, with its own rules, buildings, mobility services, and dedicated security officials and devices. Many features and services involved in a smart city are also essential in the context of a smart campus. Existing research studies have proposed several assessment schemes for smart cities. A recent study [48] provided a comprehensive review of 34 assessment schemes with typological statistics on the smart city indicators. However, there is a lack of literature focussing on the indicator set for the smart campus. Therefore, this paper tries to rethink the prioritised smart city indicators and map their concepts into the smart campus context, from which the smart campus indicators can be established with reliable references to the coherent context.

The persistent indicators in the technology dimension are collected from the widely recognised themes in smart cities. The themes are economy, people, governance, environment, living, and mobility, which are the six main pillars of smart cities. The technological indicators with higher weights in each theme are selected from the smart cities indicator list. In this selection, an indicator is recognised as ‘technological’ when it refers to the current deployment or the future planning of smart technologies rather than emphasising its influences on other dimensions such as environment and well-being. For example, the percentage of buildings with renewable power generation would be a technological indicator, whereas the annual energy saving indicator is non-technological as it represents the resultant benefit of the deployment of renewable energy facilities. Nevertheless, the themes related to the concretised goals of smart cities are not necessarily applicable to the context of the smart campus. Considering the shrunk functionalities and the specific objectives of smart campuses as compared to smart cities, we re-categorise these selected technological indicators into three domains to suit smart campuses, which are smart environment, smart education, and smart infrastructure. By doing so, the assessment schemes for smart cities are translated into the technological indicators and the three domains in the context of the smart campus.

The identified technological indicators and their classification are shown in Table 1. By contrast to the qualitative indicators in Ref. [48], we have converted them into quantitative indicators to enable numerical computation and analysis. In some situations, multiple smart campus indicators can be generated from one qualitative indicator in the smart city scope.

### 3.3 | Suggested indicators in sustainability dimension

Similar to the technology dimension, many frameworks and indices for sustainability assessment have been proposed at the smart city level. Most of them are designed on the SDG guideline where the goal is to maintain the balance between the economy, environment, and society domains. Technical innovations in the city and campus contexts can either promote or constrain the development in these three domains. For instance, the use of renewable power generation technologies contributes to environmental sustainability in terms of lower greenhouse gas emissions but could decrease economic efficiency in the short term. The deployment of the high-density sensing technologies in IoT networks helps improve learning and living efficiencies, but the inappropriate use of sensors may raise personal privacy concerns. With the technology revolution in the ‘smart’ era, the complex interactions among the three sustainability domains must be investigated. This could be achieved by rationally identifying and quantifying the indicators to represent the technology-driven influences and impacts in each domain, followed by multi-criteria structural analysis.

The sustainability indicators for smart campus assessment as shown in Table II are extracted from the smart city indicators in Ref. [48] with adjustment and rearrangement. Since the smart city indicators provided in Ref. [48] are not specified for sustainability assessment, only the indicators representing the impacts or outcomes of smart technology are selected,
which represent indicators in the sustainability dimension. Then, these smart city indicators in the conceptualised version are rethought, detailed, and quantified to suit the smart campus context. The mapping of the smart city indicators into the smart campus context can be in 1-to-1 form or 1-to-N form. The extracted sustainability indicators for the smart campus are further re-categorised into the economy, environment, and society domains to provide a clearer interpretation of SDGs emphasising the balanced development in three domains.

### 3.4 Measurement in health & well-being dimension

As previously mentioned in Section II, the H&W dimension of the proposed hybrid index mainly focuses on the SWB of school students. In the context of a smart campus, student SWB refers to a sustainable state of positive emotions and attitudes, adaptability and satisfaction with self, interpersonal relationships, and experiences at school. Student SWB is pervasive in that it affects various aspects of a student’s functioning on campus, including living, health, achievements, relationships, and safety, which requires effective subjective approaches for evaluation.

Recent research shows that the increased focus on student SWB has spurred the development of corresponding indicators, including but not limited to grit, gratitude, self-efficacy, life satisfaction, and social connectedness [49]. Based on the indicators, a number of psychological scales have also been developed and adopted in the literature to measure the SWB of students. According to Ref. [50], the Flourishing Scale and the Scale of Positive and Negative Experience are used for measuring and predicting the well-being of university students. The Satisfaction with Life Scale and the Positive and Negative Affect Schedule have also been used in multiple articles [51, 52]. In Australia, the Personal Well-being Index—School children [53] was developed according to a self-administered and multi-item scale for measuring the personal well-being of students, which covers all the items of happiness corresponding to school life. In Ref. [54], a screening scale named General Health Questionnaire for measuring students’ stress levels was used to make a positive impact on the medical students’ mental health. A domain-specific scale has been developed in Ref. [47] to address the unique relations between personality and various aspects of college students’ mental health. Moreover, many literatures have combined multiple scales to comprehensively evaluate SWB [49, 51]. In this paper, to avoid a biased judgement, we are not going to provide suggestions on the indicators and scales for SWB measure. The selection of SWB indicators and scales would be different across schools and regions, depending on school characteristics, development strategies, and regional policies.

### 4 Potential applications of hybrid index

The proposed hybrid framework is designed on a comprehensive multi-dimensional architecture incorporating technologies, sustainability, and H&W aspects that are essential in evaluating a smart campus. The index derived from this framework should have a broad application potential. In this section, we discuss potential applications that the hybrid index and its framework can fit.
4.1 Smart campus benchmark

From the previous review, it can be seen that the existing indices always focus on a specific aspect and there is no index comprehensively considering all of the technology, sustainability, and H&W. Also, current industry benchmarks are limited to reflect the smartness level of smart campuses. This not only increases the difficulty of formulating smart campus solutions but also prevents the effects of the corresponding solutions from being well evaluated. By having the ability to comprehensively evaluate smart campuses, the proposed hybrid framework and index can bridge these gaps. In addition, the hybrid index has significance for the implementation of potential activities. For example, the index can provide a smartness ranking of smart campuses, which is an effective and efficient way to fairly reflect the smartness level. With the ranking and competition mechanism, a better ranking will become a strong qualification for the continuous, balanced, and stable development of the campuses, which will spur educational institutions to keep pace with the times and innovate their works, to improve the index. Therefore, in the long run, the hybrid index can be deemed as a reliable reference and benchmark to promote the development of smart campuses.

TABLE 2  Suggested indicators in sustainability dimension

| Domain                               | Impact factor in smart city context | Suggested indicators in smart campus context | Unit          | Contribution |
|--------------------------------------|------------------------------------|---------------------------------------------|--------------|--------------|
| Economy                              | Income level                       | Total number of enrolment                    | #            | +            |
|                                      |                                    | Enrolment per sustainability-related course  | +            |              |
|                                      | Employment/unemployment rate       | Total number of employees                    | +            |              |
| Environment                          | Proportion of recycled waste       | Campus waste per capita                      | tons         | −            |
|                                      |                                    | Campus recycling per capita                   | tons         | −            |
|                                      |                                    | Campus recycling/campus waste                | %            | +            |
| Air quality                          |                                    | Campus PM-2.5 level per capita               | lbs          | −            |
|                                      |                                    | Campus PM-10 level per capita                | −            |              |
|                                      |                                    | Campus SO2 level per capita                  | −            |              |
| Greenhouse gas (GHG) emissions       |                                    | Campus GHG emissions per capita              | MTCO2E kg    | −            |
|                                      |                                    | Campus CH4 level per capita                  | %            | −            |
|                                      |                                    | Total green space/total campus area          | +            |              |
| Annual water consumption             |                                    | Campus water use per capita                  | Gal          | −            |
|                                      |                                    | Campus water recycled per capita             | Gal          | −            |
|                                      |                                    | Campus water recycled/campus water use       | %            | +            |
| Annual energy consumption            |                                    | Campus energy use per capita                 | MMBtu        |              |
|                                      |                                    | Campus electricity purchased per capita      | kwh          | −            |
|                                      |                                    | Campus natural gas purchased per capita      | CCF          | −            |
|                                      |                                    | Campus energy purchased/campus energy use    | %            | −            |
| Society                              | Ethnic, cultural, and gender equality | Non-residency rate in enrolment              | %            | +            |
| Individual safety and security       | Number of crimes                   | #                                           | −            |              |
|                                      | Number of larcenies                | −                                           |              |              |
| Community safety and crime rate      | Number of on crimes on campus      | #                                           | −            |              |
|                                      | Number of fire incidents on campus | −                                           |              |              |
| Road traffic efficiency, travel time, congestion levels, congestion management | Transportation energy consumption per capita | MMBtu | − | |
| Efficient access level to public transport | Number of campus bicycle racks per capita | # | + | |
|                                      | Campus bus ridership/number of buses | ratio | − | |
4.2 | Smart campus planning and roadmap

As the construction of a smart campus involves stakeholders, environmental conditions, equipment resources, and social factors, various educational institutions have certain subjectivity and deviations in the smart development objectives. The hybrid index involves technology, sustainability, and well-being, which can provide a more balanced solution to be used as an ultimate goal for developing smart campus, leading various educational institutions to formulate smart development plans and strategies. For example, if the contribution from the technology dimension is weak then the decision-makers need to check the latest technologies and consider using them should they enhance the overall smartness. However, if H&W contribution drops, more relevant resources may need to be added, such as introducing new curriculum and counselling activities and services to boost H&W. The hybrid index can serve as an optimisation objective with the process that never hinders the campus from meeting their requirements and inherent constraints, such as the rigid requirements on limited facilities and local policies.

This application is not only about the campus's one-time optimisation, but also about the campus's future long-term planning and roadmaps. In addition, various prediction methods can be seamlessly connected with the index to achieve a forward-looking index to meet the formulation of future roadmaps.

4.3 | Template for other fields in smart cities

In developing smart cities, technologies, sustainability, and well-being are also common and valuable aspects to be considered. A smart campus resembles a small-scale smart city, which reflects that a logical extension of the concept and principle of the hybrid framework is also applicable in many other fields of smart cities. In other words, the proposed hybrid framework can provide templates for various fields of smart cities, allowing more vision of smartness and its implications. For example, in the development of smart energy as a crucial part of smart cities, various cutting-edge technologies, such as renewable energy sources, energy storage, and smart meters, are increasingly integrated, with associated influences on the economy, environment, and society, as well as bringing benefits and constraints to the well-being of energy users as customers. In this smart energy context, the proposed hybrid framework can be applied to assess the performance of its smartness process as long as the indicators are appropriately adjusted to reflect the key considerations in smart energy. This will contribute to increasing the utilisation rate of renewable energy and energy storage systems and also contribute to reducing energy-related carbon footprint, without impairing or even benefiting users' well-being. From a macro perspective, the proposed hybrid framework provides a fundamental reference for ongoing works towards formulating a global index to objectively measure and rank smart cities.

5 | CASE STUDIES ON COVID-19 IMPACT

The coronavirus (COVID-19) disease has recently caused a global pandemic and it has infected over 256 million people and claimed the lives of over 5.13 million people (as of 19 September 2021) since December 2019. Under the pandemic of COVID-19, campus closure has been intermittently implemented across 188 countries around the world, which has affected the well-being of hundreds of millions of students. Owing to its remote, personalised, and ubiquitous features, the smart campus has shown unprecedented importance to cope with the impact and challenges of the long-term school closure. This section presents a case study that investigates the multi-dimensional impacts of COVID-19 on educational institutions by using the proposed hybrid assessment framework on the public data of a university in the United States to calculate and compare the derived index immediately before and during the COVID-19 pandemic. This case study also aims to validate the rationality of the proposed hybrid index.

5.1 | Data specifications

The university data is collected partially from the annual enrolment reports, partially from the annual environmental metrics, and partially from Ref. [52]. A database over a decade from 2011 to 2021 is used to scale contributions from each indicator. The indicator values with minimum and maximum contributions over these 10 years are set as 0 and 1, respectively. The financial year 2019 and 2020 data from annual enrolment reports and the annual environmental metrics is extracted to calculate the contributions from the technology and sustainability dimension. Due to the lack of campus historical data on student SWB, we use the data in Refs. [52, 55] as national-scale data to reflect the contributions from the H&W dimension in US colleges before and during the COVID-19 pandemic.

5.2 | Visualisation of assessment results

The assessment is firstly carried out in each dimension, and then the hybrid index is calculated by incorporating the contributions from individual dimensions using (2). The indicator values in each dimension are presented in radar diagrams Figures 2-4, respectively, where the movement of indicators in response to the COVID-19 pandemic can be observed. It can be seen that the impacts of the COVID-19 pandemic on individual indicators are in different ways.

In the technology dimension, the contributions from some indicators represent the deployment level of smart technologies and facilities, including smart campus-related research funding, smart energy management, penetration of renewable electricity, smart lighting, smart air-quality control, smart temperature control, and sensing facilities. Their contributions are slightly increased, which indicates the steady deployment of
smart technologies on campus. In the sustainability dimension, the impact of the pandemic can be viewed from the three sustainability domains (i.e. economy, environment, and society) independently. The indicators in these three domains change in different ways. As shown in Figure 3, the indicators in the economy domain (i.e. the green sector) are reduced while most of the indicators in the environment domain (i.e. the yellow section) are improved. In the society domain, the indicators show deviated patterns. The enrolment-related indicators are reduced while the indicators related to crime and security are improved. In the H&W dimension, Cantril Scale [56] is used to measure the student's well-being. This scale conceptualises well-being into 5 domains: career, community, financial, physical, and social. The variations of contributions from individual domains are shown in Figure 4. The pentagon formed up by the five domains is shrunken in all domains, which indicates the reduction in student H&W.

Based on the indicator values, the contribution from each dimension to the overall hybrid index is calculated and shown in Figure 5. Before the pandemic, the contributions from technology and H&W dimensions are higher than that from the sustainability dimension. The COVID-19 lockdown pandemic has obviously changed the shape of this triangle, where the sustainability contribution becomes outstanding but
with a negative impact on student H&W. Moreover, the overall hybrid index is calculated as 0.281 before the pandemic and 0.327 during the pandemic. This small increase means the impact of the COVID-19 lockdown pandemic on the smart campus development is overall insignificant.

5.3 | Discussion and remarks

In the assessment results of this study, the variations of most indicators have shown a reasonable trend that can be explained by the common impacts of the lockdown pandemic. In the technology dimension, the network-related issues such as outages and incidents increased, so that the contributions from these indicators dropped. This phenomenon could be explained as the increased stress on the internal network as more students and staff use the network remotely. The number of wireless clients on campus dropped due to the lack of access. The use of an online learning facility, as shown by the indicators ‘online learning enrolment’ and ‘average daily hours of learning with the aid of smart technology’, significantly increased, which implies the boosted need for remote learning services during the lockdown period. In the sustainability dimension, the economic indicators are reduced during the pandemic due to the lockdown of the national board and unemployment in the recession. The environment indicators are mostly improved during the pandemic, which shows the opposite variation trend as compared to the economy domain. This phenomenon is rational as the less population and workload on campus will result in a reduction in waste, emissions, and resource consumption. For the society domain, the indicators representing equalities are reduced due to the travelling difficulties for international students. Nevertheless, the indicators on crimes and incidents on campus are greatly improved as the lockdown sharply cut off the campus population and thus the chance of crimes and incidents. In the H&W dimension, the impacts on social and community domains are more significant than the other three, probably caused by the social isolation during the lockdown period.

Moreover, the synergy among the three dimensions can also be observed from the results. In the sustainability domain, although there is a significant improvement in ‘campus waste per capita’ and ‘campus recycling per capita’ indicators, the increase in the ‘campus recycling/campus waste’ indicator is much weaker. In this situation, the reason behind the boost in ‘per capita” indicators could be the reduction of people on campus during the lockdown period, but the slightly higher ratio value between recycling waste and total waste is synergically caused by the improvement in smart waste technology on campus. A similar trend is also shown among the indicators ‘campus energy use per capita’, ‘campus electricity purchased per capita’, ‘campus natural gas purchased per capita’, and ‘campus energy purchased/campus energy use’, where the increase in ‘campus energy purchased/campus energy use’ indicator synergically reflects the influence of higher penetration of renewable electricity production as shown in the technology dimension. Another synergy shown in the results is that, while the lockdown pandemic shows considerable benefits on sustainability, the student H&W has also been significantly impaired. This means the lockdown outbreak has to some extent broken the original balance among the three dimensions before the pandemic.

In this study, the COVID-19 pandemic is shown as the primary driver of the variations in the three dimensions and the hybrid index, and in the meantime, the synergy effects among the three dimensions are also observable. As compared to the existing metric systems concerning a single dimension or domain, such as Refs. [22–47], the proposed assessment framework serves as a platform to provide a broader vision of the different essential aspects and their co-effects, which could generate information in a wider scope to facilitate smart campus planning and development.

6 | CONCLUSION AND OUTLOOK

This paper proposes a hybrid assessment framework for the smart campus. This framework integrates the contributions from three dimensions, which are technology capability, sustainability, and student H&W, aiming to provide a multi-dimensional view of campus smartness for human-centred sustainable development. A hybrid index is obtained as an
outcome of the proposed framework, which provides a composite measure of the overall smartness of the campus, together with the assessment in each dimension to demonstrate their synergy and balancing condition. The proposed framework and index have been applied to the historical data of a university in the United States, both before and during the COVID-19 pandemic, to investigate the variation of the assessment index in response to the lockdown outbreak. The assessment results show that the outbreak significantly improves the sustainability contribution but negatively impairs students’ H&W. The indicator changes in different dimensions demonstrate a reasonable trend during the pandemic period, and in the meantime, the synergy effects among the indicators in different dimensions are also demonstrated. These results indicate the rationality of the proposed hybrid framework and index for smart campus assessment, owing to its capability to provide a more comprehensive vision of the different essential aspects as well as their co-effects, which would be beneficial for the decision-makers of educational institutions to develop more accurate and balanced solutions on smart campus planning and roadmap. The smart campus assessment work presented in this paper would also provide a research template to inform the development of smart cities and their sub-systems that need a smart revolution.

Based on the smart campus assessment framework and index proposed in this paper, future research opportunities lie in several directions. Firstly, stakeholders’ H&W related to the smart revolution in educational institutions could be more precisely defined and evaluated to better suit the new framework and index designed for smart campus assessment. Secondly, smart campus planning methodologies could be further reinforced to consider the balance of the three dimensions raised in this paper. Lastly, multi-dimensional assessment and planning on other smart systems, such as energy systems, health systems, transportation systems, and financial systems, also show great potential in the future for human-centred sustainable development.

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CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT
Research data are not shared.

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