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Article

Reframing Smart Campus Assessment for the Global South: Insights from Papua New Guinea

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Abstract: Higher education institutions are increasingly compelled to adapt to the demands of digital transformation. Students expect flexible, personalised, and technology-enhanced learning environments; academics require advanced infrastructure to support teaching and research; and administrators seek efficient, data-driven systems for institutional management. The smart campus paradigm has emerged as a strategic response to these evolving needs, offering a framework for digitally transforming university ecosystems. However, most existing smart campus assessment frameworks have been developed in high-income contexts and remain largely untested in the Global South, where infrastructural, financial, and technological challenges differ significantly. This study addresses this gap by evaluating the contextual relevance of a comprehensive smart campus assessment framework in a developing country setting. Focusing on the Papua New Guinea University of Technology (PNGUoT), the research uses a questionnaire survey of 278 participants to investigate their perspectives on the importance and prioritisation of performance indicators across four key dimensions: smart economy, smart society, smart environment, and smart governance. The findings affirm the overall applicability of the framework while revealing notable variations in stakeholder priorities, emphasising the need for context-sensitive and adaptable assessment tools. The study contributes to the refinement of smart campus frameworks, supporting more inclusive and responsive digital transformation strategies for higher education institutions in the Global South.

Keywords: smart campus; smart learning environments; higher education institute; university; digital transformation; technology adoption; user preferences; developing country context; assessment framework; Global South; Papua New Guinea

1. Introduction and Background

1.1. Rise of Smart Campuses in Higher Education

The accelerated advancement of digital technologies such as artificial intelligence (AI) and the Internet of Things (IoT) has significantly influenced diverse sectors, including higher education [1–3]. Universities are increasingly adopting these technologies to create smart campuses—digitally connected environments that facilitate efficient operations, personalised learning experiences, and data-informed decision-making. Emerging from smart city discourse, the smart campus concept has evolved as a compact, university-scale application of intelligent urban systems [4,5]. Within academic institutions, IoT technologies have enabled improved infrastructure management, while AI has transformed pedagogical practices and administrative processes [6,7]. This paradigm shift is further reinforced by efforts in educational informatization, where institutions seek to enhance competitiveness, institutional branding, and governance capabilities [8]. The progression from

traditional digital campuses to smart campuses is underpinned by big data analytics, integrated information systems, and automated services [9].

1.2. Defining the Smart Campus

At the core of smart campus initiatives is smart education, which transforms digital teaching and learning through the integration of mobile technologies, interactive platforms, AI-enabled systems, gamified learning tools, and augmented reality [10,11]. These innovations have the potential to improve teaching quality and student outcomes while enhancing knowledge management through IoT-based systems [12,13]. A smart campus also contributes to broader institutional goals by promoting liveability, workability, sustainability, and inclusive learning environments [14]. Advances in digital twin technologies allow campuses to visualise and simulate operations in real time, improving security, stakeholder experience, and system optimisation [15–17]. Complementary developments, such as intelligent maintenance systems combining computer-based data processing with geographic information systems (GIS), further support operational efficiency [18]. As the higher education sector aligns with Industry 4.0, smart campuses are increasingly viewed as essential for sustainable innovation, data-driven governance, and resilient infrastructure [19–21].

1.3. Evolution of Smart Campus Frameworks

Over the past decade, a range of frameworks have emerged to conceptualise and guide the development of smart campuses. Early examples, such as the iCampus and SC2 models, introduced broad, multidimensional structures encompassing governance, environment, mobility, and energy [22,23]. These foundational models were soon followed by approaches such as the Technically Driven Model and the Socio-technical 4DStock framework, which incorporated stakeholder involvement, infrastructure, and user engagement into assessments of energy and system performance [24,25]. The Smart Education Hub further expanded these concepts, integrating elements such as smart learning environments, mobility systems, hybrid instruction, and digital security [26].

More recent innovations introduced modular and ontology-based frameworks that offer structured and scalable components. These include the Smart Campus Modular Ontology framework—which classifies entities such as buildings, tools, and actors—and Augmented Reality frameworks that blend virtual and physical environments through key dimensions like smart governance and smart society [27–29]. In response to the disruptions caused by COVID-19, the field shifted toward resilience planning. Notable frameworks such as the Resilience Project Team and Smart Campus 4.0 were developed to guide universities in navigating post-pandemic recovery, ensuring continuity, and strengthening digital infrastructure [30–33].

Subsequent models have focused on integrating advanced technologies such as digital twins, cloud platforms, and Industry 4.0 and 5.0 systems to improve service quality, strategic alignment, and campus adaptability [34–36]. Among these, the Smart Campus Assessment Framework [37] presents a comprehensive structure composed of four primary dimensions—smart economy, smart society, smart environment, and smart governance—comprising a total of 48 operational indicators (Table 1).

Table 1. Smart campus assessment framework.

Dimension	Category	Indicator
Smart Economy	Business Services	Retail Services
		Recreation Services
		Art Services
	Business Efficiency	Lean Principles
		Automation Systems
		Workforce Productivity
	Utility Cost Savings	Energy Saving
		Smart Monitoring
		Maintenance

Smart Society	Innovation Ecosystem	R&D Support Innovation Hubs Industry Engagement
	Versatile Learning and Research	Responsive Curriculum Collaborative Learning Living Labs
	University Social Responsibility	Managing Social Responsibility Teaching Social Responsibility Researching Social Responsibility
	Quality Of Campus Life	Diversity and Inclusion Comfort, Safety and Security Social Interactions
	Campus Community Engagement	Communication Connection; Resources and Channels Involvement
Smart Environment	Environmentally Friendly Services	Sustainable Lifestyle Responsible Suppliers Eco-friendly Initiatives
	Renewable Energy	Energy Transformation Culture Energy Efficiency Systems Energy Best Practices
	Sustainable Development	Sustainable Policy Social Equity Partnerships for Sustainability
	Zero Waste	Waste Reduction Programs Recycling Program Incentive program
Smart Governance	Cybersecurity	Overseeing Committee Policy and Regulations Monitoring Programs
	Data Governance	Data Governance Policies Data Governance Processes Management Structures
	Decision-Making	Consultation and Collaboration Communication Practices Monitoring and Evaluation
	Service Management	Cataloguing and Design Service Delivery Efficiency Resource allocation

1.4. Knowledge and Research Gaps

Current smart campus research can be broadly grouped into three thematic categories: conceptual, technical, and sustainability-focused studies. Conceptual research investigates stakeholder perceptions and the definitional evolution of smart campuses, emphasising the varied interpretations across institutional roles [38,39]. Technical research explores specific digital innovations such as IoT-based knowledge systems, energy optimisation, digital twin platforms, and immersive learning laboratories [40,41]. Sustainability-focused research addresses the integration of smart campus principles with the United Nations Sustainable Development Goals (SDGs), including commitments to environmental stewardship and social responsibility [42,43].

Despite an expanding body of literature, few studies have developed comprehensive smart campus assessment frameworks that include clearly defined performance indicators [37]. Moreover, most existing frameworks are tailored to high-income settings, where advanced digital infrastructure and strong institutional capacity are typically present. As a result, their applicability in lower-resource environments—characterised by constrained funding, infrastructural limitations, and distinct stakeholder needs—remains uncertain, particularly for performance assessment in

developing country universities—or universities within the context of the Global South. To date, no study has systematically evaluated the applicability of smart campus frameworks in these contexts, representing a critical gap in both knowledge and research.

1.5. Research Aim and Question

This study addresses a critical and underexplored gap in the smart campus literature by evaluating the relevance and adaptability of the Smart Campus Assessment Framework within the context of the Global South. While smart campus frameworks are increasingly used to guide digital transformation in higher education, they are typically developed for high-income settings, where strong digital infrastructure, institutional capacity, and resource availability are taken for granted. These frameworks often assume conditions that do not reflect the realities faced by universities in developing countries.

Institutions in the Global South contend with a distinct set of challenges, including limited technological infrastructure, financial constraints, and diverse socio-cultural contexts. These factors can shape both the implementation and perceived value of smart campus initiatives. Despite this, few studies have examined whether existing assessment frameworks are fit for purpose in such environments. The lack of contextual validation reduces the relevance and effectiveness of these tools when applied beyond their original design contexts.

This study seeks to explore the central question: To what extent is the Smart Campus Assessment Framework relevant and adaptable for assessing smart campus development in the Global South? In doing so, it contributes to the reframing of smart campus assessment by supporting the development of more inclusive, flexible, and context-sensitive frameworks for universities in developing country settings.

2. Research Design

The research is a descriptive single-case study focussing on both single and multiple units of analysis comprising the university campus and its sections, following uses Yin’s [44] “linear but reiterative” plan (Figure 1).

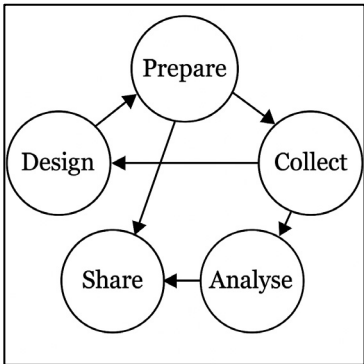


Figure 1. Case study plan.

The research follows four key stages as shown in Figure 2 below.

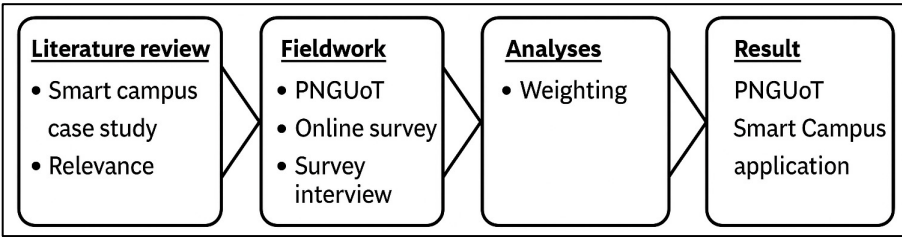


Figure 2. Descriptive case study path.

2.1. Theoretical Framework: Relevance Theory and Perception

Relevance theory involves a person's cognitive interaction with the surrounding world of contextual settings [45] expressed in perceptions [46]. Perception is argued to be a unit of relevance defined as, 'to have knowledge through the mind' or 'become conscious of or understand' something (Longman Dictionary of Contemporary English). In addition, Gilbert [47] described it as a characteristic of an agent-based model within environments undergoing a cognitive (knowledge) process by which an individual gives meaning to the environment. It is the acquisition of specific knowledge about objects or events at any moment including the interpretation of objects, symbols, and people in the light of pertinent experiences [48]. A person is motivated to improve his or her state within a context [49] and express their thoughts for their benefit [50] pursuing meanings that meet their expectations [51].

Following recent studies on relevance were conducted to measure peoples' perceptions of ideas and innovations in the education and business sector pertaining to the context of the study. Relevance studies in the education sector measured level of perception in the ethics of university graduates [52], user satisfaction and adoption of AI models of smart campus framework [53], science camps school learning environments [54], content relevance of online professional-development courses [55], and reforms in teaching and learning of science [54]. In the business sector relevance studies investigated consumer reactions to business policies and practices [56], consumers' attitudes toward marketing and marketing-related practices of business system [57], perceived quality of consumers [58,59], industrial customer expectations and performance [60], and promotional material for tourism [61].

The Likert-scale is an effective tool for measuring attitudes including perceptions. Likert-scale, was developed by Rensis Likert [62], designed to measure attitudes using a typical 5 or 7-point ordinal scale, allowing respondents to indicate their level of agreement or disagreement with the presented statement. The scale can intuitively measure people's attitudes in various contexts, with responses ranging from strongly agree to strongly disagree. However, it has limitations, such as the inability to determine individual scores on an attitude continuum. Response reliability is addressed through assigning weighting [63]. In addition, it only provides ordinal scales which is limited only to rating and ranking and lacks the ability to measure the distance between the scales.

Data that is normally distributed can allow descriptive statistics such as means, standard deviations, and parametric statistics to be calculated with the median measuring the central tendency for the Likert scale [64]. Ordinal responses on Likert-type scales require non-parametric test for analysis. Parametric tests are more robust for testing the reliability of the data [65] however, they are usually used for continuous data whereas the study's data are ordinal and discrete. Continuous data gives a changing variance between each reading, whereas ordinal data is limited in variance between each level where nonparametric tests are used [66].

2.2. Case Study Context

As the case study from the Global South context, Papua New Guinea University of Technology (PNGUoT) is selected. This is due to its representative characteristics as a public higher education institution operating within a developing country context, where infrastructural, financial, and digital limitations pose significant barriers to the implementation of smart campus initiatives. PNGUoT offers a relevant and insightful site to examine the contextual applicability of global smart campus assessment frameworks, particularly in settings that lack the robust technological infrastructure typically assumed by such models. Its campus comprises diverse academic, administrative, and support units, making it suitable for evaluating the multi-dimensional indicators of smart campus performance.

Additionally, PNGUoT has expressed institutional interest in digital transformation and sustainability, providing a timely context for stakeholder engagement on the relevance of smart campus indicators. The university's mix of students, academic staff, and professional personnel allows for triangulated insights across different roles and responsibilities. This diversity enhances the study's capacity to assess perception-driven relevance of performance indicators, supporting the

need for contextual adaptation. By focusing on PNGUoT, this study addresses a critical empirical gap and provides a grounded contribution to the refinement of inclusive and responsive smart campus strategies in the Global South.

2.3. Data Collection Instruments and Participant Sampling

The study is designed to collect data on the perspectives of key stakeholders on the relevance of 48 indicators. Three groups of stakeholders were targeted comprising: students, scholars and professional staff. Their respective perspectives may provide a more comprehensive understanding of smart campus adoption.

The single-case, descriptive study to assess the 48 indicators of the smart campus framework. A structured questionnaire based on the indicators was administered to students and staff at the selected case study university. To ensure participant comprehension and facilitate effective participation, a 5-point Likert scale question was chosen with scales ranging from 1 (Very low), 2 (Low), 3 (Neither high or low), 4 (High), to 5 (Very high). The questionnaire’s primary objective was to obtain the level of participants perceptions of the relevance of the 48 indicators. A single guiding question was asked: “How relevant do you feel the (indicator) is to the university?”. Participants then responded by indicating their perceived level of relevance. The questionnaire was designed to be completed within a 20-minute time frame.

The questionnaire was developed and distributed using Qualtrics as the online survey tool, through the university’s email system to reach all students. Anonymity was encouraged to attract a wide range of response from students across the university. For staff participants, a targeted survey was conducted with two groups: academic and professional. A total of 24 staff members were selected from the university’s human resource database based on the criteria of position (including qualifications), responsibility and length of service. Of these participants 13 were from the schools while 11 were from service sections. The three criteria were established to ensure a suitable representation of both school and sections while minimizing potential bias. focus on middle ranking positions with a wider responsibility allowed for a better understanding of the university’s operations and structure. Prioritizing individuals with longer employment periods ensured that participants had sufficient experience and a comprehensive understanding of the university’s context.

The online survey attracted over 500 student participants, with 254 providing complete responses, that were included in the data analysis. The survey interviews with the 24 staff members were executed with a few instances of confusion regarding the comprehension of the specificity of the dimensions. The issues were promptly addressed, by the interviewer, allowing the interviews to progress uninterrupted. the face-to-face interview format permitted the interviewees to extensively discuss the pros and cons of the indicators, leading to well informed response which benefited the study.

Data was sought from targeted staff [67] using survey interviews [68]. The survey approach was adopted using structured questionnaire on the forty-eight indicators of the smart campus framework due to the large number of the indicators. A 5-point Likert scale questionnaire was designed for participants to indicate their perception of the level of relevance on each of the indicators: (shown in Table 2 below). Two methods were adopted for the survey: an open online survey involving students (anonymous) campus-wide, and a targeted survey interview on selected staff in both the academic and non-academic (administration and service).

Table 2. Typical 5-point online Likert scale question.

Indicator	0 (not available)	1 (Very irrelevant)	2 (Irrelevant)	3 (Neither relevant or irrelevant)	4 (Relevant)	5 (Very relevant)
1. Retail services: Variety	☐	☐	☐	☐	☐	☐

of food, retail and other business services						
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The online campus-wide questionnaire survey was produced in Qualtrics and launched through the university’s email to all stakeholders. A link and QR Code on the survey was attached on the campus-wide email launched by the Director of ICT. It provided an open, anonymous and voluntary approach removing any biases towards a group or person to generalize the survey for the case study. It ran for a period of two months where a total of 254 participants responded.

A face-to-face survey using semi-structured interview was conducted targeting academic and non-academic staff representing the functions of the university comprising, 13 schools and 11 sections, a total of 24 staff.

Table 3. Target interview survey questions.

School / section: Estates and services	0 (not available)	1 (Very irrelevant)	2 (Irrelevant)	3 (Neither relevant or irrelevant)	4 (Relevant)	5 (Very relevant)
1. Retail services: Variety of food, retail and other business services	☐	☐	☐	☐	☐	☐

3. Analysis and Results

3.1. Weighting Framework

The study uses the Best-Worst Method (BWM) to assign weights to the framework's broad dimensions and categories, and Public Opinion (PO) data to estimate the relative relevance of specific indicators. The hybrid approach guarantees strategic top-down weighting while utilizing expert judgment at the indicator level, resulting in a comprehensive set of weights for each of the 48 indicators. Figure 3 displays the hierarchy of main dimensions, categories, and indicators included in the smart campus framework. The framework consists of four dimensions, 16 categories, and 48 indicators. It should be noted that for the indicator level, 278 participants scored the indicators based on a 5-point Likert scale. For the dimension and category levels, pairwise BWM questionnaires were distributed among 5 Decision-makers (DMs), and all categories and dimensions were scored using a 9-point Likert scale from a previous Delphi study [37] for relative comparison. The detailed procedure of the Hybrid BWM + PO method is as follows.



Figure 3. Smart campus framework.

3.2. Group Best-Worst Method

The Best-Worst Method (BWM) is a widely used weighting approach that derives criteria weights through pairwise comparison. The BWM determines weights based on DMs' preferences similar to the Analytic Hierarchy Process (AHP). BWM, however, has significant benefits: it needs less comparison - only $2n-3$ for n criteria as opposed to AHP's more comprehensive requirements - and it performs more consistent results [68]. The complete BWM methodology is presented as a single objective programming model (1) to simultaneously incorporate all DMs' preferences, with detailed implementation steps available in [69]:

$$\begin{aligned}
 &\min \delta_1 + \delta_2 + \dots + \delta_k \\
 &\text{st:} \\
 &\{ |W_i - a_{iw} W_w| \}_k \leq \delta_r, i=1, \dots, n, k=1, \dots, K \\
 &\{ |W_B - a_{Bi} W_i| \}_k \leq \delta_r, i=1, \dots, n, k=1, \dots, K \\
 &\sum_{i=1}^n W_i = 1
 \end{aligned} \tag{1}$$

$$W_i \geq 0$$

For the r -th DM, a_{bi} represents the preference of the best criterion over the i -th criterion, while a_{iw} denotes the preference of the i -th criterion over the worst criterion. $\{ \}_k$ indicates the constraints that pertain specifically to the k -th DM. The output of Model (1) consists of indicator weights determined by the DMs' judgments based on BWM questionnaires. In this model, W_i is the weight of the i -th criterion, W_w is the weight of the worst (least important) criterion, and W_b is the weight of the best (most important) criterion.

3.3. Public Opinion Method

The PO method is a participatory approach used to gather and analyse expert or stakeholder judgments for weighting, ranking, or decision-making [70]. PO relies on subjective inputs from experts to assess the importance of criterion/indicators. In general, PO-based weights can be obtained by opinion polling, which is both simple and cost-effective [71]. Weights can be derived from expert surveys, Likert-scale ratings, or direct scoring rather than mathematical optimization. Based on the PO method, the normalized weight (w_i) for i -th criterion/indicator can be calculated using Equation (2):

$$w_i = \frac{\text{Mean Score of Criterion } i}{\sum_{j=1}^n \text{Mean Score of Criterion } j} \quad (2)$$

3.4. Results

The Hybrid BWM + PO method is applied to calculate the importance weights of dimensions, categories, and indicators within the smart campus framework. As previously stated, the group BWM approach is used for determining weights at the dimension and category levels, whereas the PO method is used for indicator-level weighting. We distribute two types of questionnaires for pairwise comparisons - a BWM questionnaire based on a 9-point Likert scale system (with responses from 5 DMs) and PO rating questionnaires based on a 5-point Likert scale system (with responses from 278 experts). The weighting results for each level will be discussed individually in the following sections.

3.4.1. Dimension-Level Weighting

In general, at this level, the 5 DMs compared "Smart Economy" (Criterion 1), "Smart Society" (Criterion 2), "Smart Environment" (Criterion 3), and "Smart Governance" (Criterion 4) with each other using the 9-point Likert scale system. According to Model 1, we have the following Problem (3):

$$\min \text{TI} = \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5$$

st:

$$W_1, W_2, W_3, W_4 \geq 0$$

$$W_1 + W_2 + W_3 + W_4 = 1$$

$$\text{DM 1 (Best: Smart Environment } (W_3), \text{ Worst: Smart Society } (W_2)) \quad (3)$$

$$|W_3 - 3 W_1| \leq \delta_1, |W_3 - 5 W_2| \leq \delta_1, |W_3 - 3 W_4| \leq \delta_1$$

$$|W_1 - 4 W_2| \leq \delta_1, |W_4 - 5 W_2| \leq \delta_1$$

$$\text{DM 2 (Best: Smart Governance } (W_4), \text{ Worst: Smart Society } (W_2))$$

$$|W_4 - 4 W_1| \leq \delta_2, |W_4 - 5 W_2| \leq \delta_2, |W_4 - 3 W_3| \leq \delta_2$$

$$|W_1 - 3 W_2| \leq \delta_2, |W_3 - 4 W_2| \leq \delta_2$$

DM 3 (Best: Smart Governance (W_4), Worst: Smart Environment (W_3))

$$|W_4 - 5 W_1| \leq \delta_3, |W_4 - 4 W_2| \leq \delta_3, |W_4 - 5 W_3| \leq \delta_3$$
$$|W_1 - 2 W_3| \leq \delta_3, |W_2 - 2 W_3| \leq \delta_3$$

DM 4 (Best: Smart Governance (W_4), Worst: Smart Economy (W_1))

$$|W_4 - 4 W_1| \leq \delta_4, |W_4 - 7 W_2| \leq \delta_4, |W_4 - 3 W_3| \leq \delta_4$$
$$|W_2 - 6 W_1| \leq \delta_4, |W_3 - 4 W_1| \leq \delta_4$$

DM 5 (Best: Smart Governance (W_4), Worst: Smart Economy (W_1))

$$|W_4 - 7 W_1| \leq \delta_5, |W_4 - 3 W_2| \leq \delta_5, |W_4 - 3 W_3| \leq \delta_5$$
$$|W_2 - 2 W_1| \leq \delta_5, |W_3 - 5 W_1| \leq \delta_5$$

We implemented the above problem in a Python environment using the Pyomo library. The importance weights of each dimension in the smart campus framework were obtained by minimizing the Total Inconsistency (TI) via Problem (3). Table 4 and Figure 4 show the importance weights of each dimension in the smart campus framework. Accordingly, “Smart Governance” has the highest weight and importance, followed by “Smart Environment”. For “Smart Economy” and “Smart Society”, equal weight importance was achieved.

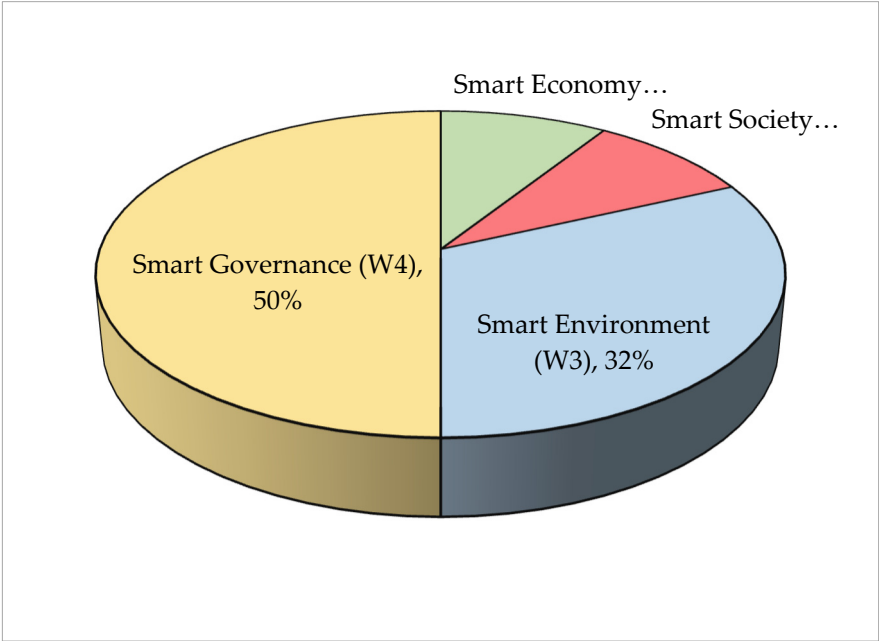


Figure 4. The relative importance of smart campus dimensions.

Table 4. The importance weights of smart campus dimensions.

Dimension	Weight
Smart Economy	W_1 : 0.0909
Smart Society	W_2 : 0.0909
Smart Environment	W_3 : 0.3182
Smart Governance	W_4 : 0.5000

Similar to the previous section, all categories within each dimension of the Smart Campus framework were separately compared based on the questionnaires from five decision-makers (DMs).

The weights for each group were derived using the BWM model. Note that all weights obtained in these groups are calculated within their respective dimensions. To determine the overall weight of a specific category relative to all categories across all dimensions, we must also consider the dimension weights calculated in the previous section. The overall weights will be computed for obtaining subgroup weights within each dimension is as follows:

3.4.2. Smart Economy Weighting

At this level, the 5 DMs compared “Business services” (Criterion 1), “Business efficiency” (Criterion 2), “Utility cost savings” (Criterion 3), and “Innovation ecosystem” (Criterion 4) with each other using the 9-point Likert scale system. According to Model 1, we have the following Problem (4):

$$\min TI = \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5$$

st:

$$W_1, W_2, W_3, W_4 \geq 0$$

$$W_1 + W_2 + W_3 + W_4 = 1$$

DM 1 (Best: Innovation ecosystem (W_4), Worst: Business services (W_1))

$$|W_4 - 5 W_1| \leq \delta_1, |W_4 - 3 W_2| \leq \delta_1, |W_4 - 4 W_3| \leq \delta_1$$

$$|W_2 - 4 W_1| \leq \delta_1, |W_3 - 3 W_1| \leq \delta_1$$

DM 2 (Best: Business efficiency (W_2), Worst: Business services (W_1))

$$|W_2 - 5 W_1| \leq \delta_2, |W_2 - 3 W_3| \leq \delta_2, |W_2 - 2 W_4| \leq \delta_2$$

$$|W_3 - 3 W_1| \leq \delta_2, |W_4 - 4 W_1| \leq \delta_2$$

(4)

DM 3 (Best: Innovation ecosystem (W_4), Worst: Business services (W_1))

$$|W_4 - 6 W_1| \leq \delta_3, |W_4 - 2 W_2| \leq \delta_3, |W_4 - 4 W_3| \leq \delta_3$$

$$|W_2 - 5 W_1| \leq \delta_3, |W_3 - 3 W_1| \leq \delta_3$$

DM 4 (Best: Business efficiency (W_2), Worst: Utility cost savings (W_3))

$$|W_2 - 6 W_1| \leq \delta_4, |W_2 - 6 W_3| \leq \delta_4, |W_2 - 3 W_4| \leq \delta_4$$

$$|W_1 - 2 W_3| \leq \delta_4, |W_4 - 3 W_3| \leq \delta_4$$

DM 5 (Best: Business efficiency (W_2), Worst: Business services (W_1))

$$|W_2 - 5 W_1| \leq \delta_5, |W_2 - 3 W_3| \leq \delta_5, |W_2 - 2 W_4| \leq \delta_5$$

$$|W_3 - 2 W_1| \leq \delta_5, |W_4 - 4 W_1| \leq \delta_5$$

Table 5 and Figure 5 display the relative importance weights of the categories in the Smart Economy dimension. “Business efficiency” ranks highest with a weight of 0.4417, followed by

"Innovation ecosystem" at 0.3655. Conversely, "Business services" has the lowest weight at just 0.0763, indicating its minimal impact in this category.

Table 5. The importance weights of smart economy categories.

Category	Weight
Business services	W_1 : 0.0763
Business efficiency	W_2 : 0.4417
Utility cost savings	W_3 : 0.1165
Innovation ecosystem	W_4 : 0.3655

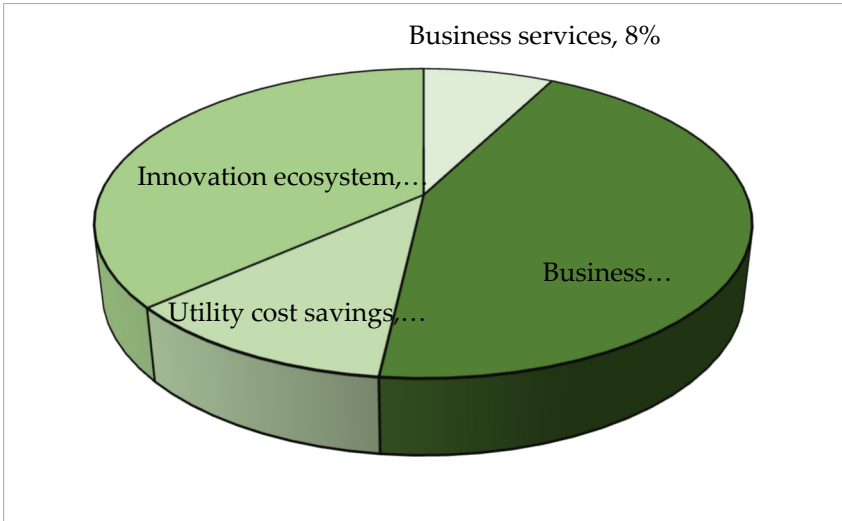


Figure 5. The relative importance of smart economy categories. .

3.4.3. Smart Society Weighting

At this stage, the five DMs evaluated and compared four key criteria: “Versatile learning and research” (Criterion 1), “University social responsibility” (Criterion 2), “Utility cost savings” (Criterion 3), and “Campus community engagement” (Criterion 4). The comparison was conducted using a 9-point Likert scale system. Based on Model 1, we derive the following optimization problem (Problem (5)):

Table 6 and Figure 6 present the importance weights of categories within the Smart society dimension. Among these, "Versatile learning and research" holds the highest weight (0.4615), indicating its dominant role. "Utility cost savings" and "Campus community engagement" share equal weights, suggesting comparable significance. In contrast, "University social responsibility" has the lowest weight (0.0769), reflecting its relatively minor influence in this dimension.

$$\min TI= \delta_1+\delta_2+\delta_3 +\delta_4+\delta_5$$

st:

$$W_1, W_2,W_3,W_4\geq 0$$
$$W_1+W_2+W_3+W_4=1$$

(5)

DM 1 (Best: Campus community engagement (W_4), Worst: University social responsibility (W_2))

$$|W_4- 5 W_1|\leq \delta_1, |W_4- 3 W_2|\leq \delta_1, |W_4- 4 W_3|\leq \delta_1$$
$$|W_2- 4 W_1|\leq \delta_1, |W_3- 3 W_1|\leq \delta_1$$

DM 2 (Best: Campus community engagement (W_4), Worst: University social responsibility (W_2))

$|W_2-5\ W_1|\leq \delta_2, |W_2-3\ W_3|\leq \delta_2, |W_2-2\ W_4|\leq \delta_2$
 $|W_3-3\ W_1|\leq \delta_2, |W_4-4\ W_1|\leq \delta_2$

DM 3 (Best: Versatile learning and research (W_1), Worst: University social responsibility (W_2))

$|W_4-6\ W_1|\leq \delta_3, |W_4-2\ W_2|\leq \delta_3, |W_4-4\ W_3|\leq \delta_3$
 $|W_2-5\ W_1|\leq \delta_3, |W_3-3\ W_1|\leq \delta_3$

DM 4 (Best: Versatile learning and research (W_1), Worst: University social responsibility (W_2))

$|W_2-6\ W_1|\leq \delta_4, |W_2-6\ W_3|\leq \delta_4, |W_2-3\ W_4|\leq \delta_4$
 $|W_1-2\ W_3|\leq \delta_4, |W_4-3\ W_3|\leq \delta_4$

DM 5 (Best: Versatile learning and research (W_1), Worst: University social responsibility (W_2))

$|W_1-5\ W_2|\leq \delta_5, |W_1-3\ W_3|\leq \delta_5, |W_1-3\ W_4|\leq \delta_5$
 $|W_3-3\ W_2|\leq \delta_5, |W_4-4\ W_2|\leq \delta_5$

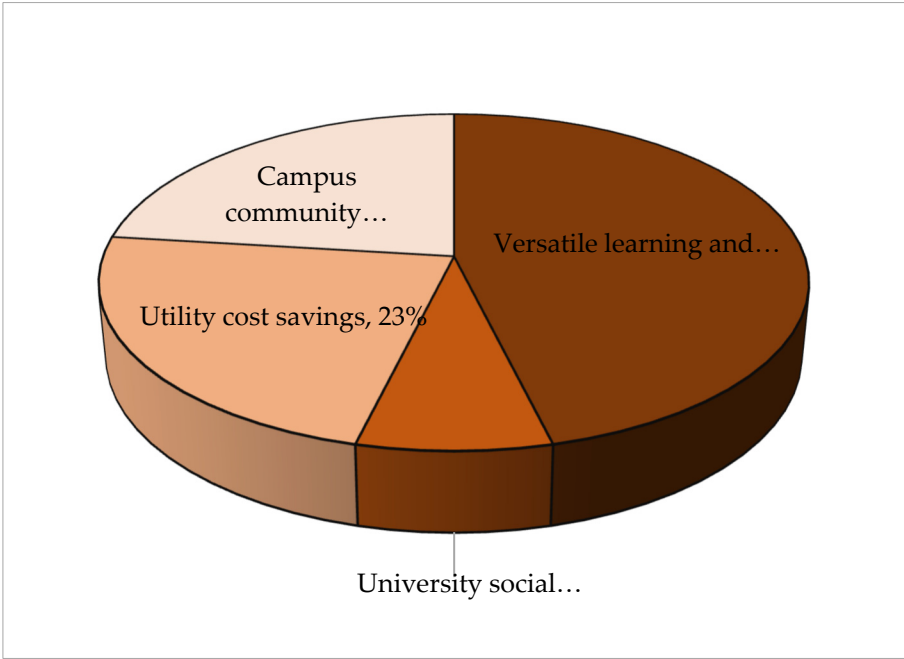


Figure 6. The relative importance of smart society categories.

Table 6. The importance weights of smart society categories.

Category	Weight
Versatile learning and research	W_1 : 0.4615
University social responsibility	W_2 : 0.0769
Utility cost savings	W_3 : 0.2308

Campus community engagement	W ₄ : 0.2308
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3.4.4. Smart Environment Weighting

At this level, the five DMs evaluated and compared four key categories: “Environmentally friendly services” (Criterion 1), “Renewable energy” (Criterion 2), “Sustainable development” (Criterion 3), and “Zero waste” (Criterion 4). The comparison was conducted using a 9-point Likert scale system. Based on Model 1, we derive the following optimization problem (Problem (6):

$$\begin{aligned} \min \text{TI} &= \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 \\ \text{st:} \\ W_1, W_2, W_3, W_4 &\geq 0 \\ W_1 + W_2 + W_3 + W_4 &= 1 \end{aligned}$$

DM 1 (Best: Sustainable development (W_3), Worst: Zero waste (W_4))

$$\begin{aligned} |W_3 - 2W_1| &\leq \delta_1, |W_3 - 3W_2| \leq \delta_1, |W_3 - 5W_4| \leq \delta_1 \\ |W_1 - 3W_4| &\leq \delta_1, |W_2 - 3W_4| \leq \delta_1 \end{aligned}$$

DM 2 (Best: Environmentally friendly services (W_1), Worst: Zero waste (W_4))

$$\begin{aligned} |W_1 - 2W_2| &\leq \delta_2, |W_1 - 3W_3| \leq \delta_2, |W_1 - 6W_4| \leq \delta_2 \\ |W_2 - 4W_4| &\leq \delta_2, |W_3 - 5W_4| \leq \delta_2 \end{aligned} \tag{6}$$

DM 3 (Best: Sustainable development (W_3), Worst: Zero waste (W_4))

$$\begin{aligned} |W_3 - 2W_1| &\leq \delta_3, |W_3 - 2W_2| \leq \delta_3, |W_3 - 6W_4| \leq \delta_3 \\ |W_1 - 5W_4| &\leq \delta_3, |W_2 - 3W_4| \leq \delta_3 \end{aligned}$$

DM 4 (Best: Environmentally friendly services (W_1), Worst: Zero waste (W_4))

$$\begin{aligned} |W_1 - 3W_2| &\leq \delta_4, |W_1 - 3W_3| \leq \delta_4, |W_1 - 9W_4| \leq \delta_4 \\ |W_2 - 6W_4| &\leq \delta_4, |W_3 - 6W_4| \leq \delta_4 \end{aligned}$$

DM 5 (Best: Renewable energy (W_2), Worst: Zero waste (W_4))

$$\begin{aligned} |W_2 - 3W_1| &\leq \delta_5, |W_2 - 3W_3| \leq \delta_5, |W_2 - 6W_4| \leq \delta_5 \\ |W_1 - 4W_4| &\leq \delta_5, |W_3 - 3W_4| \leq \delta_5 \end{aligned}$$

The relative importance of each category in the Smart Environment dimension is shown in Table 7 and Figure 7. The top-weighted factors are "Environmentally friendly services," "Renewable energy," and "Sustainable development," each scoring 0.3. On the other hand, "Zero waste" has the lowest weighting (0.1), indicating its limited impact within this dimension.

Table 7. The importance weights of smart environment categories.

Category	Weight
Environmentally friendly services	W ₁ : 0.3000
Renewable energy	W ₂ : 0.3000
Sustainable development	W ₃ : 0.3000
Zero waste	W ₄ : 0.1000

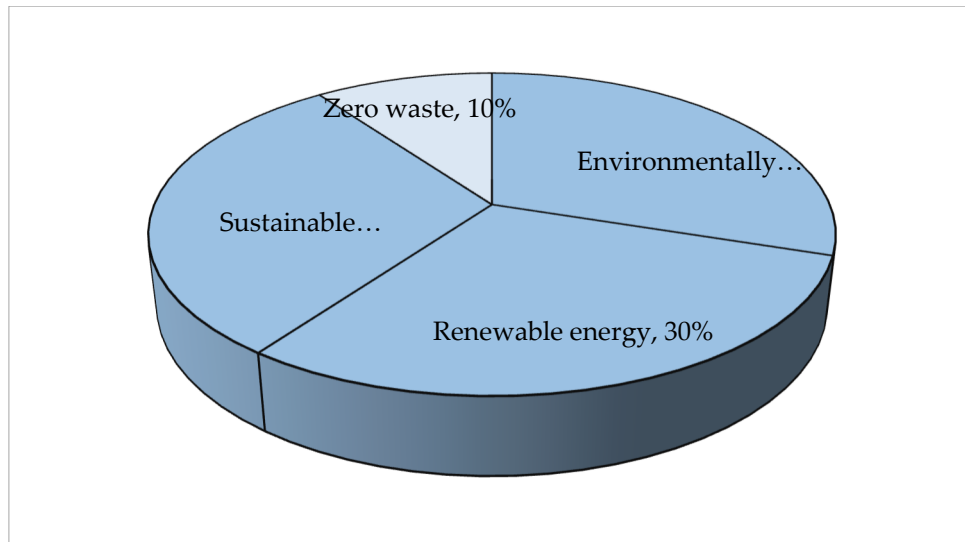


Figure 7. The relative importance of smart environment categories.

3.4.5. Smart Governance Weighting

At this stage, the five DMs assessed and ranked four critical categories: (1) "Cybersecurity", (2) "Data governance", (3) "Decision-making", and (4) "Service management". Following the framework of Model 1, we formulate the optimization challenge presented in Problem (7).

$$\min TI = \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5$$

st:

$$W_1, W_2, W_3, W_4 \geq 0$$

$$W_1 + W_2 + W_3 + W_4 = 1$$

DM 1 (Best: Data governance (W_2), Worst: Service management (W_4))

$$|W_2 - 3W_1| \leq \delta_1, |W_2 - 2W_3| \leq \delta_1, |W_2 - 9W_4| \leq \delta_1$$

$$|W_1 - 8W_4| \leq \delta_1, |W_3 - 5W_4| \leq \delta_1$$

DM 2 (Best: Decision-making (W_3), Worst: Cybersecurity (W_1))

$$|W_3 - 8W_1| \leq \delta_2, |W_3 - 7W_2| \leq \delta_2, |W_3 - 6W_4| \leq \delta_2$$

$$|W_2 - 6W_1| \leq \delta_2, |W_4 - 5W_1| \leq \delta_2$$

DM 3 (Best: Decision-making (W_3), Worst: Data governance (W_2))

$$|W_3 - 4W_1| \leq \delta_3, |W_3 - 6W_2| \leq \delta_3, |W_3 - 2W_4| \leq \delta_3$$

$$|W_1 - 2W_2| \leq \delta_3, |W_4 - 4W_2| \leq \delta_3$$

DM 4 (Best: Decision-making (W_3), Worst: Cybersecurity (W_1))

$$|W_3 - 3W_1| \leq \delta_4, |W_3 - 7W_2| \leq \delta_4, |W_3 - 4W_4| \leq \delta_4$$

$$|W_2 - 7W_1| \leq \delta_4, |W_4 - 4W_1| \leq \delta_4$$

DM 5 (Best: Decision-making (W_3), Worst: Service management (W_4))

(7)

$$|W_3-4\ W_1|\leq \delta_5, |W_3-2\ W_2|\leq \delta_5, |W_3-5\ W_4|\leq \delta_5$$
$$|W_1-2\ W_4|\leq \delta_5, |W_2-3\ W_4|\leq \delta_5$$

The relative importance of categories in the Smart Governance dimension is illustrated in Table 8 and Figure 8. "Decision-making" emerges as the most influential factor with a weight of 0.6410, demonstrating its predominant role. The secondary categories, "Service management" and "Data governance," show nearly identical weights (ranking second and third respectively), indicating similar levels of importance. Conversely, "Cybersecurity" carries the lowest weight (0.07796), suggesting it plays a substantially smaller role within this governance framework.

Table 8. The importance weights of smart governance categories.

Category	Weight
Cybersecurity	W_1 : 0.077960
Data governance	W_2 : 0.138595
Decision-making	W_3 : 0.641001
Service management	W_4 : 0.142445

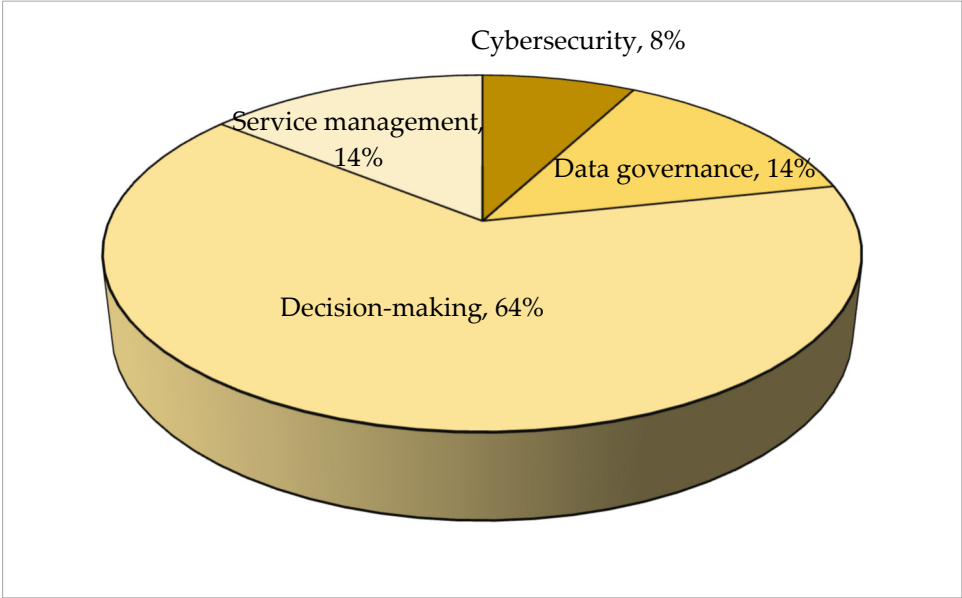


Figure 8. The relative importance of smart governance categories.

3.4.6. Indicator-Level Weighting

In this stage, we calculate the importance weights of all 48 indicators within their respective categories. As previously mentioned, the study employs the PO (Prioritization and Optimization) method for these calculations. A total of 278 respondents scored each indicator using a 5-point Likert scale system. Note that all weights are calculated relative to their specific categories. To determine the overall weights of indicators across all categories (accounting for both category and dimension weights), additional calculations are required. Table 9 shows the mean scores and the corresponding calculated weights for all indicators, derived using the PO method. The weight for each individual indicator was determined by dividing its mean score by the total mean score of its respective category. For example, the weight for the "Relevance Levels of Art Services" indicator is calculated by dividing its score of 1.6942 by the Total mean category score of 7.0935, resulting in a weight of 0.2388.

Table 9. The importance weights of indicators within their subgroups.

Dimensions	Categories	Indicators	All participants		Students		Scholars		Administrative/ professional staff	
			Mean score	Indicator weight	Mean score	Indicator weight	Mean score	Indicator weight	Mean score	Indicator weight
1. Smart economy	1. Business services	1. Relevance Levels of Retail Services	2.6403	0.3722	2.6102	0.3679	2.7692	0.3871	3.1818	0.4545
		2. Relevance Levels of Recreation Services	2.7590	0.3889	2.7874	0.3929	2.6923	0.3763	2.1818	0.3117
		3. Relevance Levels of Art Services	1.6942	0.2388	1.6969	0.2392	1.6923	0.2366	1.6364	0.2338
	2. Business efficiency	4. Relevance Levels of Lean Principles	2.2419	0.3426	2.2016	0.3428	2.2308	0.3258	3.1818	0.3535
		5. Relevance Levels of Automation Systems	1.9029	0.2908	1.8819	0.2930	1.9231	0.2809	2.3636	0.2626
		6. Relevance Levels of Workforce Productivity	2.3993	0.3666	2.3386	0.3641	2.6923	0.3933	3.4545	0.3838
	3. Utility cost savings	7. Relevance Levels of Energy Saving	1.8597	0.3293	1.8583	0.3255	1.7692	0.3898	2.0000	0.3607
		8. Relevance Levels of Smart Monitoring	1.7230	0.3051	1.8346	0.3214	0.4615	0.1017	0.6364	0.1148
		9. Relevance Levels of Maintenance	2.0647	0.3656	2.0157	0.3531	2.3077	0.5085	2.9091	0.5246
	4. Innovation ecosystem	10. Relevance Levels of R & D Support	2.1619	0.3223	2.1890	0.3218	2.0000	0.3333	1.7273	0.3220
		11. Relevance Levels of Innovation Hubs	2.0468	0.3051	2.1181	0.3113	1.0769	0.1795	1.5455	0.2881
		12. Relevance Levels Industry Engagement	2.5000	0.3727	2.4961	0.3669	2.9231	0.4872	2.0909	0.3898
2. Smart society	5. Versatile learning and research	13. Relevance Levels of Responsive Curriculum	2.5576	0.3128	2.5787	0.3143	2.6154	0.2931	2.0000	0.3014
		14. Relevance Levels of Collaborative Learning	2.5360	0.3102	2.5157	0.3066	3.0000	0.3362	2.4545	0.3699
		15. Relevance Levels of Living Labs	3.0827	0.3770	3.1102	0.3791	3.3077	0.3707	2.1818	0.3288
	6. University social responsibility	16. Relevance Levels of Managing Social Responsibility	2.6835	0.3531	2.6496	0.3509	3.0000	0.3391	3.0909	0.4250
		17. Relevance Levels of Teaching Social Responsibility	2.4281	0.3195	2.3976	0.3175	3.3077	0.3739	2.0909	0.2875
		18. Relevance Levels of Researching Social Responsibility	2.4892	0.3275	2.5039	0.3316	2.5385	0.2870	2.0909	0.2875
	7. Quality of campus life	19. Relevance Levels of Diversity and Inclusion	3.0216	0.3540	2.9528	0.3583	3.8462	0.3311	3.6364	0.3101
		20. Relevance Levels of Comfort, Safety and Security	2.6691	0.3127	2.5394	0.3082	4.1538	0.3576	3.9091	0.3333
		21. Relevance Levels of Social Interactions	2.8453	0.3333	2.7480	0.3335	3.6154	0.3113	4.1818	0.3566
	8. Campus community engagement	22. Relevance Levels of Communication	2.8165	0.3355	2.7283	0.3352	3.6923	0.3357	3.8182	0.3415
		23. Relevance Levels of Connection; Resources and Channels	2.8381	0.3381	2.7638	0.3395	3.5385	0.3217	3.7273	0.3333
		24. Relevance Levels of Involvement	2.7401	0.3264	2.6482	0.3253	3.7692	0.3427	3.6364	0.3252
3. Smart environment	9. Environmentally friendly services	25. Relevance Levels of Sustainable Lifestyle	2.4604	0.3629	2.3622	0.3484	3.6923	0.4898	3.2727	0.5538
		26. Relevance Levels of Responsible Suppliers	2.2410	0.3305	2.2402	0.3304	2.8462	0.3776	1.5455	0.2615
		27. Relevance Levels of Eco-friendly Initiatives	2.0791	0.3066	2.1772	0.3211	1.0000	0.1327	1.9091	0.1846
	10. Renewable energy	28. Relevance Levels of Energy Transformation Culture	2.0755	0.3706	2.0906	0.3602	1.9231	0.5319	1.9091	0.5833
		29. Relevance Levels of Energy Efficiency Systems	1.8453	0.3295	1.9252	0.3318	1.0000	0.2766	1.0000	0.3056
		30. Relevance Levels of Energy Best Practices	1.6799	0.2999	1.7874	0.3080	0.6923	0.1915	0.3636	0.1111
	11. Sustainable development	31. Relevance Levels of Sustainable Policy	2.1223	0.3141	2.1693	0.3235	1.3846	0.2045	1.9091	0.2414
		32. Relevance Levels of Social Equity	2.5288	0.3743	2.4843	0.3705	3.0000	0.4432	3.0000	0.3793
		33. Relevance Levels of Partnerships for Sustainability	2.1047	0.3115	2.0514	0.3060	2.3846	0.3523	3.0000	0.3793
	12. Zero waste	34. Relevance Levels of Waste Reduction Programs	1.9101	0.3753	1.9252	0.3679	1.6154	0.5122	1.9091	0.4667
		35. Relevance Levels of Recycling Program	1.7590	0.3456	1.7913	0.3424	1.2308	0.3902	1.6364	0.4000
		36. Relevance Levels of Incentive program	1.4209	0.2792	1.5157	0.2897	0.3077	0.0976	0.5455	0.1333

4. Smart governance	13. Cybersecurity	37. Relevance Levels of Overseeing Committee	1.6799	0.3273	1.7874	0.3290	0.7692	0.3846	0.2727	0.1429
		38. Relevance Levels of Policy and Regulations	1.7338	0.3378	1.8268	0.3362	0.6154	0.3077	0.9091	0.4762
		39. Relevance Levels of Monitoring Programs	1.7194	0.3350	1.8189	0.3348	0.6154	0.3077	0.7273	0.3810
	14. Data governance	40. Relevance Levels of Data Governance Policies	2.1367	0.3006	2.1496	0.3012	1.4615	0.2754	2.6364	0.3085
		41. Relevance Levels of Data Governance Processes	2.2014	0.3097	2.2047	0.3089	1.4615	0.2754	3.0000	0.3511
		42. Relevance Levels of Management Structures	2.7698	0.3897	2.7835	0.3900	2.3846	0.4493	2.9091	0.3404
	15. Decision-making	43. Relevance Levels of Consultation and Collaboration in Decision-making	2.7410	0.3230	2.6339	0.3199	3.4615	0.3462	4.3636	0.3478
		44. Relevance Levels of Communication Practices in Decision-making	3.0971	0.3650	3.0118	0.3659	3.6923	0.3692	4.3636	0.3478
		45. Relevance Levels of Monitoring and Evaluation in Decision-making	2.6475	0.3120	2.5866	0.3142	2.8462	0.2846	3.8182	0.3043
	16. Service management	46. Relevance Levels of Cataloguing and Design in Decision-making	2.6871	0.3383	2.6142	0.3377	3.2308	0.3387	3.7273	0.3475
		47. Relevance Levels of Service Delivery Efficiency in Decision-making	2.5899	0.3261	2.4882	0.3215	3.4615	0.3629	3.9091	0.3644
		48. Relevance Levels of Resource allocation in Decision-making	2.6655	0.3356	2.6378	0.3408	2.8462	0.2984	3.0909	0.2881

3.4.7. Overall Category and Indicator Weights

The overall weights are now calculated for both categories and indicators, making it possible to compare the relative importance of all indicators and categories with respect to each other. Table 10 presents the overall weights of all criteria at each level. For the calculations, the overall weights of categories are obtained using Equation (8): we multiply each category’s weight by the weight of its respective dimension. For example, to calculate the overall weight of the Business Services category, we multiply its category weight (0.0763) by the weight of the dimension it belongs to - Smart Economy (0.0909) - which results in 0.0069. To calculate the overall weight of an indicator, based on Equation (9), we multiply the indicator’s weight by the weights of its respective category and dimension. For example, to calculate the overall weight of the Relevance Levels of Retail Services indicator, we multiply its weight (0.3722) by the weights of the Business Services category (0.0763) and the Smart Economy dimension (0.0909), which results in 0.0026. Table 11 ranks the categories and indicators by overall weight. Based on this, the results for all participants across the three levels of the Smart Campus framework are summarised below.

Category overall weight = Weight_{Dimension} × Weight_{Category} (8)

Indicator overall weight = Weight_{Dimension} × Weight_{Category} × Weight_{Indicator} (9)

Dimension-Level

In the Smart Campus framework, at the dimension level, it can be observed that Smart Governance is the most important dimension, followed by Smart Environment. Both Smart Economy and Smart Society dimensions are equally important but rank lower in significance compared to the other dimensions.

Category-Level

Within the Smart Campus framework's category-level analysis, Decision-making (from the Smart Governance dimension) emerges as the most significant category. This is followed in importance by Environmentally Friendly Services, Renewable Energy, and Sustainable Development from the Smart Environment category. In contrast, Business Services (under Smart Economy) demonstrates relatively lower importance compared to other categories.

Indicator-Level

At the indicator level of the Smart Campus framework, "Relevance Levels of Communication Practices in Decision-making" (Decision-making category) ranks as the most significant indicator. The subsequent highest-ranking indicators are "Relevance Levels of Consultation and Collaboration in Decision-making" and "Relevance Levels of Monitoring and Evaluation in Decision-making". Conversely, "Relevance Levels of Art Services" (Business Services category) shows comparatively lower importance among all indicators.

Table 10. Overall importance weights of criteria in smart campus framework.

Dimension	Category	Category overall weight	Indicator	All participants		Students		Scholars		Administrative/ professional staff	
				Indicator weight	Indicator overall weight	Indicator weight	Indicator overall weight	Indicator weight	Indicator overall weight	Indicator weight	Indicator overall weight
1. Smart economy, W: 0.0909	1. Business services, W: 0.0763	0.0069	1. Relevance Levels of Retail Services	0.3722	0.0026	0.3679	0.0026	0.3871	0.0027	0.4545	0.0032
			2. Relevance Levels of Recreation Services	0.3889	0.0027	0.3929	0.0027	0.3763	0.0026	0.3117	0.0022
			3. Relevance Levels of Art Services	0.2388	0.0017	0.2392	0.0017	0.2366	0.0016	0.2338	0.0016
	2. Business efficiency, W: 0.4417	0.0402	4. Relevance Levels of Lean Principles	0.3426	0.0138	0.3428	0.0138	0.3258	0.0131	0.3535	0.0142
			5. Relevance Levels of Automation Systems	0.2908	0.0117	0.2930	0.0118	0.2809	0.0113	0.2626	0.0105
			6. Relevance Levels of Workforce Productivity	0.3666	0.0147	0.3641	0.0146	0.3933	0.0158	0.3838	0.0154
	3. Utility cost savings, W: 0.1165	0.0106	7. Relevance Levels of Energy Saving	0.3293	0.0035	0.3255	0.0034	0.3898	0.0041	0.3607	0.0038
			8. Relevance Levels of Smart Monitoring	0.3051	0.0032	0.3214	0.0034	0.1017	0.0011	0.1148	0.0012
			9. Relevance Levels of Maintenance	0.3656	0.0039	0.3531	0.0037	0.5085	0.0054	0.5246	0.0056
	4. Innovation ecosystem, W: 0.3655	0.0332	10. Relevance Levels of R & D Support	0.3223	0.0107	0.3218	0.0107	0.3333	0.0111	0.3220	0.0107
			11. Relevance Levels of Innovation Hubs	0.3051	0.0101	0.3113	0.0103	0.1795	0.0060	0.2881	0.0096
			12. Relevance Levels Industry Engagement	0.3727	0.0124	0.3669	0.0122	0.4872	0.0162	0.3898	0.0130
2. Smart society, W: 0.0909	5. Versatile learning and research, W: 0.4615	0.0420	13. Relevance Levels of Responsive Curriculum	0.3128	0.0131	0.3143	0.0132	0.2931	0.0123	0.3014	0.0126
			14. Relevance Levels of Collaborative Learning	0.3102	0.0130	0.3066	0.0129	0.3362	0.0141	0.3699	0.0155
			15. Relevance Levels of Living Labs	0.3770	0.0158	0.3791	0.0159	0.3707	0.0156	0.3288	0.0138
	6. University social responsibility, W: 0.0769	0.0070	16. Relevance Levels of Managing Social Responsibility	0.3531	0.0025	0.3509	0.0025	0.3391	0.0024	0.4250	0.0030
			17. Relevance Levels of Teaching Social Responsibility	0.3195	0.0022	0.3175	0.0022	0.3739	0.0026	0.2875	0.0020
			18. Relevance Levels of Researching Social Responsibility	0.3275	0.0023	0.3316	0.0023	0.2870	0.0020	0.2875	0.0020
	7. Quality of campus life, W: 0.2308	0.0210	19. Relevance Levels of Diversity and Inclusion	0.3540	0.0074	0.3583	0.0075	0.3311	0.0069	0.3101	0.0065
			20. Relevance Levels of Comfort, Safety and Security	0.3127	0.0066	0.3082	0.0065	0.3576	0.0075	0.3333	0.0070
			21. Relevance Levels of Social Interactions	0.3333	0.0070	0.3335	0.0070	0.3113	0.0065	0.3566	0.0075
	8. Campus community engagement, W: 0.2308	0.0210	22. Relevance Levels of Communication	0.3355	0.0070	0.3352	0.0070	0.3357	0.0070	0.3415	0.0072
			23. Relevance Levels of Connection; Resources and Channels	0.3381	0.0071	0.3395	0.0071	0.3217	0.0067	0.3333	0.0070
			24. Relevance Levels of Involvement	0.3264	0.0068	0.3253	0.0068	0.3427	0.0072	0.3252	0.0068
3. Smart environment, W: 0.3182	9. Environmentally friendly services, W: 0.3	0.0955	25. Relevance Levels of Sustainable Lifestyle	0.3629	0.0346	0.3484	0.0333	0.4898	0.0468	0.5538	0.0529
			26. Relevance Levels of Responsible Suppliers	0.3305	0.0315	0.3304	0.0315	0.3776	0.0360	0.2615	0.0250
			27. Relevance Levels of Eco-friendly Initiatives	0.3066	0.0293	0.3211	0.0307	0.1327	0.0127	0.1846	0.0176
	10. Renewable energy, W: 0.3	0.0955	28. Relevance Levels of Energy Transformation Culture	0.3706	0.0354	0.3602	0.0344	0.5319	0.0508	0.5833	0.0557
			29. Relevance Levels of Energy Efficiency Systems	0.3295	0.0315	0.3318	0.0317	0.2766	0.0264	0.3056	0.0292
			30. Relevance Levels of Energy Best Practices	0.2999	0.0286	0.3080	0.0294	0.1915	0.0183	0.1111	0.0106
	11. Sustainable development, W: 0.3	0.0955	31. Relevance Levels of Sustainable Policy	0.3141	0.0300	0.3235	0.0309	0.2045	0.0195	0.2414	0.0230
			32. Relevance Levels of Social Equity	0.3743	0.0357	0.3705	0.0354	0.4432	0.0423	0.3793	0.0362
			33. Relevance Levels of Partnerships for Sustainability	0.3115	0.0297	0.3060	0.0292	0.3523	0.0336	0.3793	0.0362
	12. Zero waste, W: 0.1	0.0318	34. Relevance Levels of Waste Reduction Programs	0.3753	0.0119	0.3679	0.0117	0.5122	0.0163	0.4667	0.0148
			35. Relevance Levels of Recycling Program	0.3456	0.0110	0.3424	0.0109	0.3902	0.0124	0.4000	0.0127
			36. Relevance Levels of Incentive program	0.2792	0.0089	0.2897	0.0092	0.0976	0.0031	0.1333	0.0042
4. Smart governance, W: 0.5	13. Cybersecurity, W: 0.0780	0.0390	37. Relevance Levels of Overseeing Committee	0.3273	0.0128	0.3290	0.0128	0.3846	0.0150	0.1429	0.0056
			38. Relevance Levels of Policy and Regulations	0.3378	0.0132	0.3362	0.0131	0.3077	0.0120	0.4762	0.0186
			39. Relevance Levels of Monitoring Programs	0.3350	0.0131	0.3348	0.0130	0.3077	0.0120	0.3810	0.0148
	14. Data governance, W: 0.1386	0.0693	40. Relevance Levels of Data Governance Policies	0.3006	0.0208	0.3012	0.0209	0.2754	0.0191	0.3085	0.0214
			41. Relevance Levels of Data Governance Processes	0.3097	0.0215	0.3089	0.0214	0.2754	0.0191	0.3511	0.0243
			42. Relevance Levels of Management Structures	0.3897	0.0270	0.3900	0.0270	0.4493	0.0311	0.3404	0.0236
	15. Decision-making, W: 0.6410	0.3205	43. Relevance Levels of Consultation and Collaboration in Decision-making	0.3230	0.1035	0.3199	0.1025	0.3462	0.1109	0.3478	0.1115
			44. Relevance Levels of Communication Practices in Decision-making	0.3650	0.1170	0.3659	0.1173	0.3692	0.1183	0.3478	0.1115
			45. Relevance Levels of Monitoring and Evaluation in Decision-making	0.3120	0.1000	0.3142	0.1007	0.2846	0.0912	0.3043	0.0975
	16. Service management, W: 0.1424	0.0712	46. Relevance Levels of Cataloguing and Design in Decision-making	0.3383	0.0241	0.3377	0.0241	0.3387	0.0241	0.3475	0.0247
			47. Relevance Levels of Service Delivery Efficiency in Decision-making	0.3261	0.0232	0.3215	0.0229	0.3629	0.0258	0.3644	0.0260
			48. Relevance Levels of Resource allocation in Decision-making	0.3356	0.0239	0.3408	0.0243	0.2984	0.0213	0.2881	0.0205

Table 11. Ranking of weights for indicators.

Indicator	All participants		Students		Scholars		Administrative/ professional staff	
	Overall	Ra	Overall	Ran	Overall	Rank	Overall	Rank
	weight	nk	weight	k	weight		weight	
Relevance Levels of Communication Practices in Decision-making	0.11698	1	0.11726	1	0.11834	1	0.11148	1
Relevance Levels of Consultation and Collaboration in Decision-making	0.10353	2	0.10254	2	0.11094	2	0.11148	2
Relevance Levels of Monitoring and Evaluation in Decision-making	0.10000	3	0.10070	3	0.09122	3	0.09754	3
Relevance Levels of Social Equity	0.03573	4	0.03537	4	0.04231	6	0.03621	6
Relevance Levels of Energy Transformation Culture	0.03538	5	0.03439	5	0.05078	4	0.05569	4
Relevance Levels of Sustainable Lifestyle	0.03464	6	0.03326	6	0.04676	5	0.05287	5
Relevance Levels of Responsible Suppliers	0.03155	7	0.03154	8	0.03604	7	0.02497	10
Relevance Levels of Energy Efficiency Systems	0.03145	8	0.03167	7	0.02640	10	0.02917	8
Relevance Levels of Sustainable Policy	0.02999	9	0.03088	9	0.01953	14	0.02304	14
Relevance Levels of Partnerships for Sustainability	0.02974	10	0.02921	12	0.03363	8	0.03621	7
Relevance Levels of Eco-friendly Initiatives	0.02927	11	0.03066	10	0.01266	25	0.01762	18
Relevance Levels of Energy Best Practices	0.02863	12	0.02940	11	0.01828	17	0.01061	29
Relevance Levels of Management Structures	0.02700	13	0.02702	13	0.03113	9	0.02359	13
Relevance Levels of Cataloguing and Design in Decision-making	0.02410	14	0.02405	15	0.02412	12	0.02475	11
Relevance Levels of Resource allocation in Decision-making	0.02390	15	0.02427	14	0.02125	13	0.02052	16
Relevance Levels of Service Delivery Efficiency in Decision-making	0.02322	16	0.02290	16	0.02585	11	0.02595	9
Relevance Levels of Data Governance Processes	0.02146	17	0.02140	17	0.01908	15	0.02433	12
Relevance Levels of Data Governance Policies	0.02083	18	0.02087	18	0.01908	16	0.02138	15
Relevance Levels of Living Labs	0.01582	19	0.01590	19	0.01555	21	0.01379	24
Relevance Levels of Workforce Productivity	0.01472	20	0.01462	20	0.01579	20	0.01541	20
Relevance Levels of Lean Principles	0.01375	21	0.01376	21	0.01308	24	0.01419	23
Relevance Levels of Policy and Regulations	0.01317	22	0.01311	23	0.01199	28	0.01856	17
Relevance Levels of Responsive Curriculum	0.01312	23	0.01318	22	0.01230	27	0.01264	27
Relevance Levels of Monitoring Programs	0.01306	24	0.01305	24	0.01199	29	0.01485	21
Relevance Levels of Collaborative Learning	0.01301	25	0.01286	25	0.01410	23	0.01552	19
Relevance Levels of Overseeing Committee	0.01276	26	0.01282	26	0.01499	22	0.00557	38
Relevance Levels Industry Engagement	0.01238	27	0.01219	27	0.01619	19	0.01295	25

Relevance Levels of Waste Reduction Programs	0.01194	28	0.01171	29	0.01630	18	0.01485	22
Relevance Levels of Automation Systems	0.01167	29	0.01177	28	0.01128	30	0.01054	30
Relevance Levels of Recycling Program	0.01100	30	0.01089	30	0.01242	26	0.01273	26
Relevance Levels of R & D Support	0.01071	31	0.01069	31	0.01107	31	0.01070	28
Relevance Levels of Innovation Hubs	0.01014	32	0.01034	32	0.00596	38	0.00957	31
Relevance Levels of Incentive program	0.00888	33	0.00922	33	0.00310	41	0.00424	40
Relevance Levels of Diversity and Inclusion	0.00743	34	0.00752	34	0.00695	35	0.00651	37
Relevance Levels of Connection; Resources and Channels	0.00709	35	0.00712	35	0.00675	36	0.00699	35
Relevance Levels of Communication	0.00704	36	0.00703	36	0.00704	34	0.00716	33
Relevance Levels of Social Interactions	0.00699	37	0.00700	37	0.00653	37	0.00748	32
Relevance Levels of Involvement	0.00685	38	0.00683	38	0.00719	33	0.00682	36
Relevance Levels of Comfort, Safety and Security	0.00656	39	0.00647	39	0.00750	32	0.00699	34
Relevance Levels of Maintenance	0.00387	40	0.00374	40	0.00538	39	0.00556	39
Relevance Levels of Energy Saving	0.00349	41	0.00345	41	0.00413	40	0.00382	41
Relevance Levels of Smart Monitoring	0.00323	42	0.00340	42	0.00108	48	0.00122	48
Relevance Levels of Recreation Services	0.00270	43	0.00273	43	0.00261	44	0.00216	44
Relevance Levels of Retail Services	0.00258	44	0.00255	44	0.00268	42	0.00315	42
Relevance Levels of Managing Social Responsibility	0.00247	45	0.00245	45	0.00237	45	0.00297	43
Relevance Levels of Researching Social Responsibility	0.00229	46	0.00232	46	0.00201	46	0.00201	46
Relevance Levels of Teaching Social Responsibility	0.00223	47	0.00222	47	0.00261	43	0.00201	45
Relevance Levels of Art Services	0.00166	48	0.00166	48	0.00164	47	0.00162	47

4. Findings and Discussion

The results of the study highlight the potential of applying a comprehensive smart campus framework that addresses a broader range of campus features, in contrast to prior studies that have focused primarily on specific algorithms or limited aspects of campus infrastructure. Using a smart campus assessment framework comprising 48 indicators, the study demonstrated consistent relevance across the indicators, with weights ranging from 0.001 to 0.011. Notably, the combined results from the three sample groups revealed that the highest aggregated weight—approximately 0.42—was attributed to Communication Practices under the Smart Governance dimension. In contrast, the lowest weightings, around 0.01, were shared by Art Services in the Smart Economy dimension and Researching Social Responsibility in the Smart Society dimension. A general consensus among the groups indicated alignment in the perceived relevance of smart campus indicators. Figure 9 presents the aggregated relevance weights for each group, offering insights into shared and differing institutional priorities.

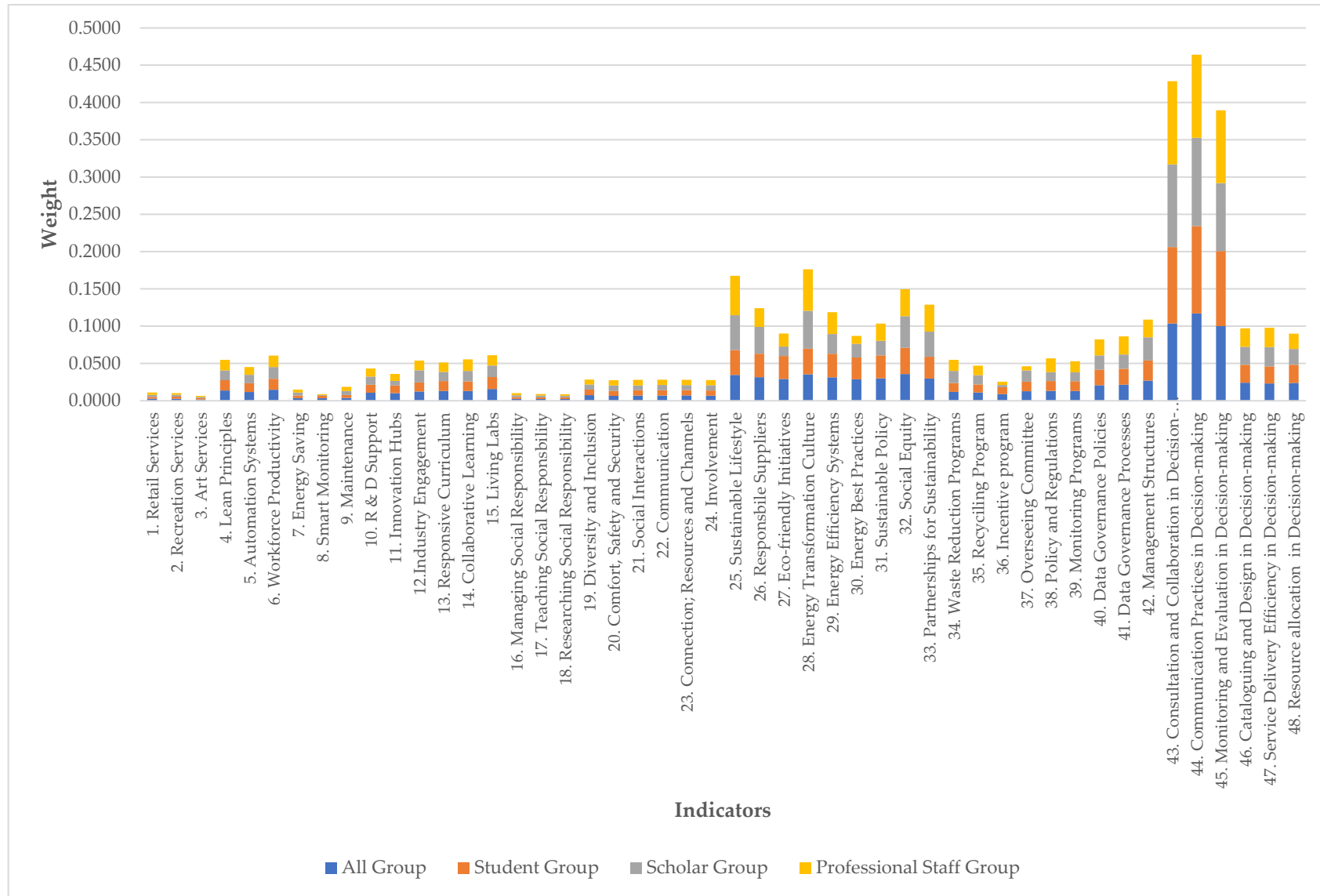


Figure 9. Groups aggregated weights. Nonetheless, the stronger performance of pedagogical indicators signals possible entry points for improvement. Curriculum reform, interdisciplinary learning environments, and lab-based pedagogy can serve as low-cost, high-impact strategies to enhance academic outcomes and graduate employability—goals consistent with sustainable smart campus development [19,21].

4.1. Smart Governance: Highest Priority Dimension

Among all four dimensions, Smart Governance emerged as the most relevant. The highest-ranking indicators—Communication Practices, Consultation and Collaboration, and Monitoring and Evaluation—belong to the “Decision-Making” category and were consistently rated the most important across all stakeholder groups. As illustrated in Figure 9, these three indicators substantially outweighed the remaining 45 in perceived importance.

This finding reflects the centrality of formal governance processes in a state-owned, bureaucratic institution like PNGUoT, where transparency, compliance, and accountability are critical [72–75]. Communication and collaborative mechanisms serve as the operational backbone, enabling routine functions such as task delegation, reporting, and institutional oversight. The strong stakeholder consensus on these indicators underscores their relevance in ensuring organisational continuity and institutional legitimacy. These results align with previous studies emphasising the foundational role of governance capabilities in digital transformation strategies within public-sector institutions [30,37,73].

4.2. Smart Environment: Sustainability as a Pragmatic Priority

Smart Environment was the second-highest rated dimension. Key indicators—Energy Transformation Culture, Sustainable Lifestyle, and Social Equity—received high relevance scores from all stakeholder groups. These indicators reflect an awareness of sustainability, energy management, and inclusive development in the face of infrastructural and financial constraints.

In the PNGUoT context, energy-saving practices and renewable energy adoption are not just environmental choices but a necessary response to limited resources [76–78]. Participants acknowledged the economic imperative of conserving energy and maintaining a sustainable campus lifestyle, particularly given the growing availability of off-grid systems and small-scale renewable solutions [77]. The high relevance of Social Equity also highlights concerns about inclusion and fairness in institutional development. This suggests that sustainability, when framed through the lenses of affordability and access, holds significant appeal—even in developing country settings [48,49].

4.3. Smart Economy: Emerging Relevance, Limited Capacity

Smart Economy was rated lowest among the four dimensions overall, but select indicators showed moderate relevance. These included Workforce Productivity, Lean Principles, and Industry Engagement from the “Business Efficiency” and “Innovation Ecosystem” categories. These findings suggest that while economic innovation is not yet a primary institutional focus, there is growing recognition of its potential.

The relatively low relevance of indicators such as Retail Services and Art Services points to the limited commercial infrastructure and entrepreneurial culture on campus. However, the moderate scores for business efficiency indicators imply a desire to improve institutional performance through streamlined processes and partnerships [79–81]. These results support literature highlighting the challenges and opportunities of innovation systems in the Global South, where institutional readiness often lags behind ambition [36,37,49].

4.4. Smart Society: Educational Relevance, Social Disconnect

Smart Society also scored relatively low overall, but with a few notable exceptions. The “Versatile Learning and Research” category received higher relevance scores, especially for Living Labs, Collaborative Learning, and Responsive Curriculum. These indicators reflect the institution’s core function as a centre for teaching and research, and stakeholder responses affirmed their value.

Despite this, indicators under the “University Social Responsibility” and “Campus Community Engagement” categories were rated less relevant. This suggests a gap between the university’s

educational mission and its broader community engagement efforts, including the perceived relevance and applicability of emerging technologies such as AI for social good. Factors such as resource scarcity, weak institutional-community linkages, limited outreach infrastructure, and nascent AI awareness or capacity may contribute to this perception [82–85].

4.5. Stakeholder Consensus: Alignment Across Institutional Roles

One of the most significant findings of this study is the strong alignment in responses across the three stakeholder groups. As shown in Figure 9, students, academics, and administrative staff demonstrated consistent prioritisation of the top indicators, particularly those related to governance and environment. This convergence enhances the robustness of the findings and suggests shared institutional understanding of the university's strategic priorities.

The observed consensus across organisational roles also indicates that stakeholders experience and interpret smart campus indicators in similar ways, increasing the framework's credibility as a planning and assessment tool. In environments with limited resources, such alignment is critical for coordinated digital transformation and reinforces the importance of inclusive stakeholder engagement in smart campus planning [37,40].

4.6. Relevance of Framework in Global South Context

While the results affirm the overall structure and applicability of the Smart Campus Assessment Framework, they also point to the importance of contextual adaptation. Governance and sustainability dimensions, which scored highest, are institutionally embedded and operationally necessary. In contrast, dimensions related to economic and social innovation require more tailored approaches.

For instance, indicators developed in high-income contexts may assume a baseline of digital infrastructure, institutional autonomy, or community integration that may not exist in lower-income settings. As a result, tools such as the framework analysed in this study must remain flexible, allowing institutions to recalibrate dimensions and indicators based on their own development stage and strategic goals [37,38,49].

This study supports calls for more inclusive and adaptive approaches to smart campus planning, especially in the Global South. The combination of top-down weighting via BWM and bottom-up validation through stakeholder perceptions offers a replicable model for other institutions aiming to contextualise global frameworks for local application.

5. Conclusion

This study critically examined the relevance and adaptability of an established Smart Campus Assessment Framework within the context of the Global South, using PNGUoT as a case study. Recognising the limitations of frameworks developed in high-income countries, this research addressed an important gap by empirically testing the framework's indicators in a setting characterised by constrained resources, infrastructural challenges, and unique sociocultural conditions. The study suggested that while the framework appears applicable, there are notable variations in stakeholder perceptions across its dimensions, highlighting the potential value of contextual adaptation.

The analysis found that Smart Governance emerged as the most relevant dimension, driven primarily by strong stakeholder consensus around decision-making processes, especially in communication practices, consultation and collaboration, and monitoring and evaluation. These results are consistent with the governance-heavy nature of PNGUoT as a public institution with a bureaucratic structure and strong accountability obligations. The high weighting of decision-making indicators reflects the institutional need for structured and transparent processes, aligning with broader expectations in developing-country universities that often operate within tight regulatory frameworks.

Smart Environment followed in perceived importance, with indicators such as energy transformation culture, sustainable lifestyle, and social equity receiving high relevance scores. This reflects a growing awareness among university stakeholders of environmental sustainability, energy efficiency, and equity, particularly in settings where financial and infrastructure limitations demand cost-saving and socially inclusive practices. The prioritisation of these environmental indicators highlights a strategic orientation towards long-term sustainability, even in resource-constrained contexts.

In contrast, Smart Economy and Smart Society were rated as equally less relevant by participants. The relatively lower emphasis on business services, retail operations, and university social responsibility suggests that economic and social innovation functions may be less developed or perceived as lower priorities within the operational realities of PNGUoT. However, several indicators—such as workforce productivity, industry engagement, and versatile learning environments—did attain moderate levels of relevance, suggesting that foundational capabilities exist that can be scaled with the right support mechanisms.

Importantly, the study found broad alignment among the three surveyed stakeholder groups—students, academics, and professional staff—in their prioritisation of indicators. This convergence enhances the reliability of the findings and indicates shared institutional values around governance and sustainability. Nonetheless, the study also acknowledges several limitations: it focused on a single case institution, did not include broader external stakeholders (e.g., government, community, suppliers), and concentrated only on perceptual data related to indicator relevance. Future research should extend this approach across diverse institutions in the Global South, integrate additional variables (e.g., technological maturity, digital literacy), and explore longitudinal dynamics of smart campus adoption.

Overall, this study contributes a much-needed empirical perspective to the literature on smart campus development in the Global South. By contextualising assessment indicators and elevating stakeholder voices, it offers a path forward for more inclusive, adaptable, and sustainable digital transformation strategies in higher education. These findings reinforce the importance of tailoring smart campus frameworks to local needs—bridging the gap between global innovation agendas and regional implementation realities.

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