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Smart Campuses: Extensive Review of the Last Decade of Research and Current Challenges

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ABSTRACT Novel intelligent systems to assist energy transition and improve sustainability can be deployed at different scales, ranging from a house to an entire region. University campuses are an interesting intermediate size (big enough to matter and small enough to be tractable) for research, development, test and training on the integration of smartness at all levels, which has led to the emergence of the concept of “smart campus” over the last few years. This review article proposes an extensive analysis of the scientific literature on smart campuses from the last decade (2010-2020). The 182 selected publications are distributed into seven categories of smartness: smart building, smart environment, smart mobility, smart living, smart people, smart governance and smart data. The main open questions and challenges regarding smart campuses are presented at the end of the review and deal with sustainability and energy transition, acceptability and ethics, learning models, open data policies and interoperability. The present work was carried out within the framework of the Energy Network of the Regional Leaders Summit (RLS-Energy) as part of its multilateral research efforts on smart regions.

INDEX TERMS Smart campus, sustainability, Internet of Things, buildings, environment, mobility, living, people, governance, data.

I. INTRODUCTION

The present work was initiated by the Energy Network of the Regional Leaders Summit (RLS). RLS is a multilateral political forum comprising seven regions of the world: Bavaria (Germany), Georgia (USA), Québec (Canada), São Paulo (Brazil), Shandong (China), Upper Austria (Austria) and the Western Cape (South Africa). The RLS-Energy network operates under the framework of RLS and aims to bring together the strengths of the different regions into joint research efforts in the field of energy [1].

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Starting from the first RLS-Sciences Conference organized by São Paulo in 2019 (a dedicated conference for the RLS-Sciences network between the political summits), the researchers have expressed a common interest for a collaboration on sustainable and smart campuses as part of their multilateral research network in order to share their diversified implementation and research experiences on that topic. The present critical literature review is part of that effort. Indeed, university campuses must be exemplary in terms of sustainable development and have a positive influence on the cities and regions in which they are located.

According to the Merriam-Webster dictionary, a campus can either be “the grounds and buildings of a university,

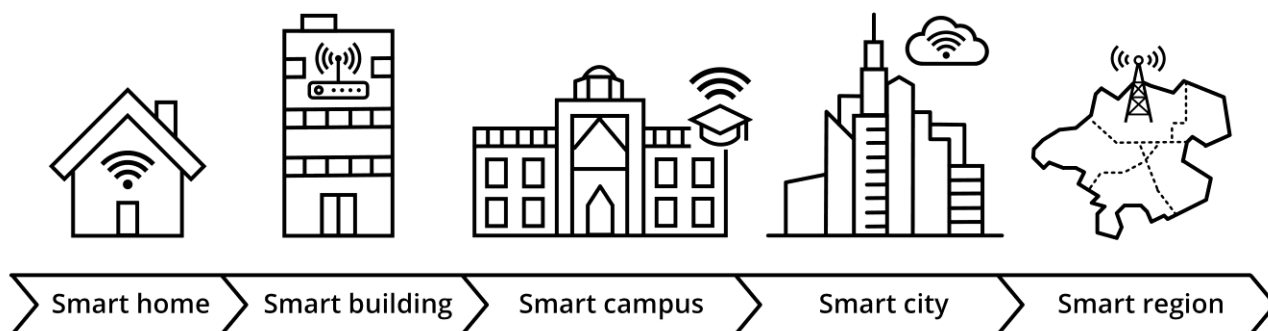


FIGURE 1. Different scales of smartness.

college, or school”, “a university, college, or school viewed as an academic, social, or spiritual entity”, or “grounds that resemble a campus” [2]. In the present work, a campus considers a set of physical infrastructures serving higher education and research.

No universal definition of “smart campus” was found in literature. However, several authors included their own definition in their publications. For example, Bandara *et al.* [3] stated that it is “an initiative to use ICT (Information and Communication Technology) within a University Campus to improve the quality and performance of the services, to reduce costs and resource consumption, and to engage more effectively and actively with its members”. Examples of said services include parking, automated attendance records and mobile applications, among others. For de Paola *et al.* [4], it is “a digitally augmented campus where pervasive instrumented objects and spaces are made responsive to the state of the environment and its inhabitants”. Similarly, Muhamad *et al.* [5] wrote that “the main role of smart campus is to present the dynamic services according to the needs of the users using some intelligence system”.

The idea of enhancing the level of smartness can be deployed at different length scales (see Fig. 1). For example, ranging from the smallest to the largest, literature presents concepts of so-called smart buildings ([6], [7]), smart neighborhoods and communities ([8], [9]), smart cities [10], smart regions [11], and so on. In each case, using information technologies and sensors, smart systems attempt to provide innovative and constantly adapting services, make better use of infrastructures and equipment, and promote communications and citizen engagement, among others. Despite the promises of “smartness”, many challenges, critics or disappointments have been encountered, indicating a clear need to continue improving our understanding of the possibilities, limits and opportunities offered by these concepts. Smart campuses are an interesting intermediate scale to elaborate, test and document ideas, hypotheses, sensors, etc. In particular, given that they are by definition places dedicated to research and innovation, universities and colleges are ideally positioned to contribute to the development of smart systems. In certain cases, the specificities of campuses in terms of services and functions (e.g., teaching, research, etc.), occupants

(e.g., students, etc.), infrastructures (e.g., microgrid, laboratories, classrooms) can require adapted smart solutions. Current literature presents brief reviews on the smart campus concept (e.g., [5]) or on specific aspects of it (e.g., [12], [13]). There is, however, a need to establish the state of the art on that topic with a broad and encompassing perspective. Therefore, this paper presents an extensive and rigorous review of the last decade of research on smart campuses and aims to cover all components of the concept critically. We follow a systematic and rigorous approach for selecting the reviewed papers with pre-established keywords and we classify the papers into seven categories based on the main question that they address. We also highlight the open questions, challenges and research opportunities, based on the analysis of literature. Last but not least, we identify sustainability efforts emerging from publications, since our vision is that a campus cannot truly be smart if it is not sustainable, and an added level of smartness can help to achieve more sustainable campuses.

The paper is structured as follows. Section II explains how the publications that were reviewed have been selected and presents a bibliometric analysis. Then, Sections III to IX summarize the main findings of the literature review, gathering publications by topic categories: smart building, smart environment, smart mobility, smart living, smart people, smart governance and smart data. A discussion section concludes the review in Section X.

II. PROCEDURE AND RESULTS OF LITERATURE REVIEW

A. SELECTION METHODOLOGY

A systematic literature review is proposed in this paper. To identify where the current research efforts lie concerning smart campuses, the inclusion criteria were kept broad, but we limited the search to university campuses. The search string (“smart campus” AND university) was used in three popular library catalogs (IEEE Xplore, ScienceDirect, and Web of Science) to select publications from the last decade, 2010 to 2020, inclusively. Then, the following publications were excluded:

- Non-peer-reviewed articles
- Articles written in a language other than English
- Books, book chapters or theses

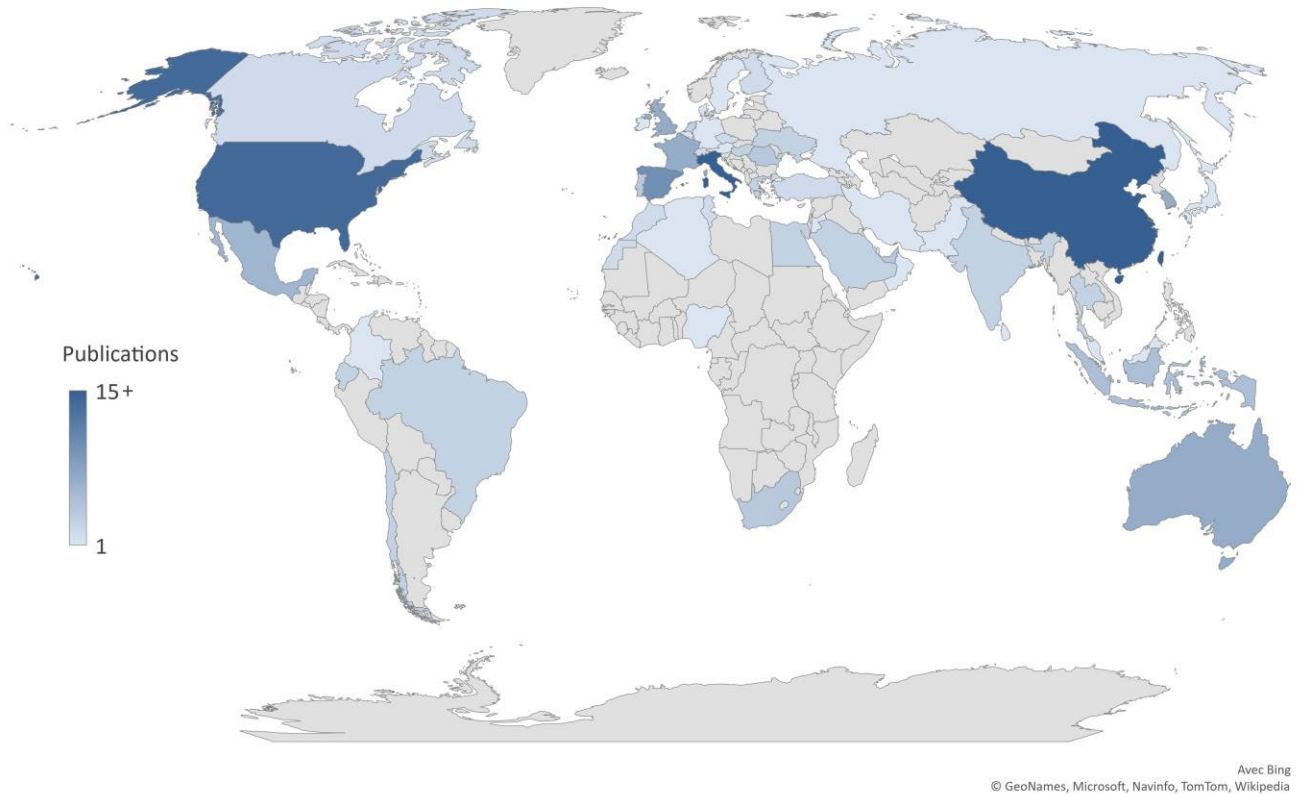


FIGURE 2. Number of publications for each country (binary count of all authors’ address).

A total of 241 publications made it through the different exclusion criteria, which remained high. After a careful analysis of each paper, when it was found that it was not directly related to the topic of “smart campus”, “intelligent campus”, or “smart university”, the article was removed from the review. The number of remaining publications was then cut down to 182, of which 90 are journal papers, and 92 are conference papers.

It is important to note that even though we have followed a rigorous approach for selecting the papers that were reviewed, it is impossible to claim that all the smart campus facets were fully covered, especially given the broad range of topics that could be linked to smart campuses. In some fields of research, it appears that the keywords “smart campus” might be less used which could have impacted the number of papers in these categories (e.g., governance, economics, teaching, etc.). Furthermore, it is also possible that a search in other and more specialized databases could have yielded other publications in these categories.

B. BIBLIOMETRIC RESULTS

This section shows bibliometric results in the form of graphics and figures. First, Fig. 2 illustrates the countries corresponding to the authors’ address, in a binary count. All continents are represented, showing the broad interest for the smart campus concept all over the world. The countries with

the highest count numbers are China (43), Italy (29), and USA (14).

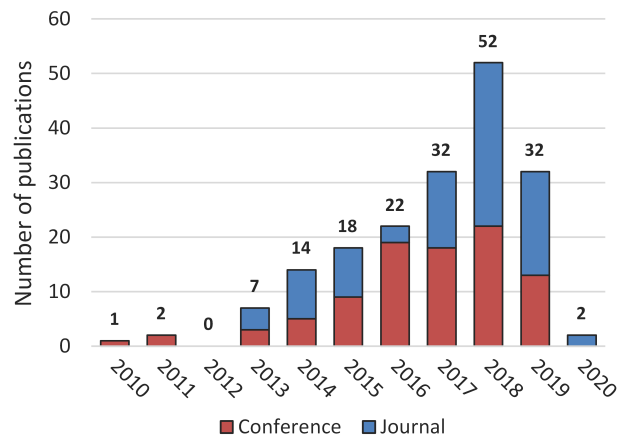


FIGURE 3. Number of selected publications per year.

In Fig. 3, it can be observed that the interest for smart campuses in literature grew exponentially over the years. The diminution of the number of papers in 2019-2020 was likely caused by the fact that some publications from 2019 had not yet been deposited in database when the review was made (i.e., early 2020). However, it is also possible that we are

witnessing a decline in interest for smart campuses or the wording could have changed over the last years.

Figure 4 displays the main technologies, devices and software solutions that were employed in the reviewed works. In Fig. 4a, the five most popular wireless communication infrastructures in the investigated literature are presented with the evolution of their use over time. The figure shows the proportion of works reporting the use of the wireless infrastructure during the period indicated on the x-axis. For example, 15% of the articles published in 2019 and 2020 mentioned using RFID (Radio Frequency Identification). Fig. 4b shows the tools reported to be used in 10 or more publications, the wireless infrastructure of Fig. 4a being excluded. The chart is dominated by the Internet of Things (henceforth named IoT), which rose strongly in popularity starting in 2016. IoT is a network of physical devices that collects and exchanges data through the Internet. Adopting an IoT platform could lead to efficient resource utilization and foster the development of artificial intelligence (AI). Next are sensors, required to make measurements and gather data. In AI, the most encountered techniques are machine learning algorithms (e.g., clustering), fuzzy logic, and artificial neural networks. Note that Apache products refer to the open-source software solutions (Hadoop, Spark, Hive, etc.) offered by the Apache Software Foundation, an American non-profit corporation.

C. FRAMEWORK FOR ANALYZING PUBLICATIONS

In order to analyze more closely the 182 publications retained for review, a framework was designed as shown in Fig. 5. It consists of seven categories of “smartness”: building, environment, mobility, living, people, governance and data. It is important to mention that even though this categorization proved to be quite convenient for analyzing literature on the smart campus concept, these categories should not be seen as hermetic. We based the framework of Fig. 5 on the concept of “smart regions” proposed by the Upper Austrian Future Academy, which is assigned to the Office of the Upper Austrian Provincial Government [14], [15]. The smart region concept had seven categories of “smartness”: living, buildings, mobility, environment, people, governance and economy. Smartness results from the intelligent combinations of the different dimensions. Two adjustments were made to gain a better correspondence with the publications related to smart campuses. First, smart economy was included as a subcategory of smart governance due to the poor coverage of both categories in literature and the fact that financial and governance aspects are often closely tied. Second, the section “smart data” was added in the present review, in order to include publications on data management, algorithms, or intelligence systems that did not refer to specific applications. Note that several authors have proposed categorizations of the smart campus concept in literature ([5], [16], [17]) that were slightly different from the present one.

A first iteration was made to classify each publication into one of the categories of smartness, based on its title and abstract. Then, after having carefully read each paper, some

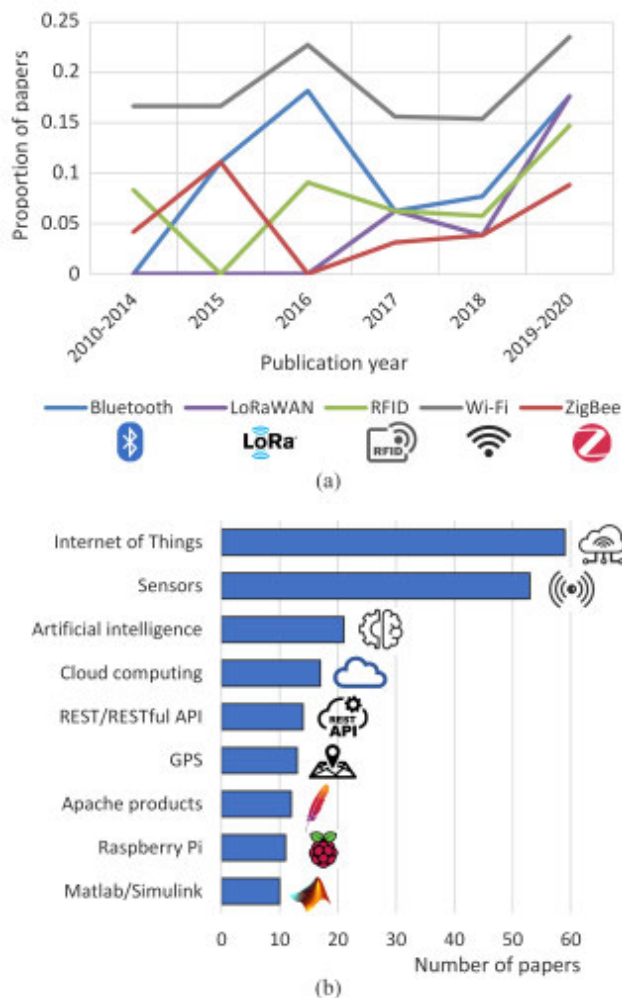


FIGURE 4. Employed technologies and tools. (a) Wireless infrastructures with respect to the year of publication; (b) Other tools used in 10 or more publications.

were changed to another category to better reflect the main topic or question that it addressed. The final number of papers in each category is reported in Fig. 5. It is important to realize that some publications could be placed in several categories. However, for the sake of simplicity, it was decided to assign each paper to only one category. Therefore, it is important to recall once again that the boundaries between the categories should not be seen as hermetic at all.

Finally, the papers in each category were thoroughly analyzed, trying to establish the common themes, key results and open questions. Excel files were used to enter all relevant information regarding each paper: authors, university, project status, technology used, framework used, key findings, etc.). Furthermore, in each smartness category, subthemes were generated to facilitate reading and highlight overarching topics. For that purpose, we used an iterative procedure, finding what was common among papers and merging similar subthemes to create the subsection titles. In this process, we tried to reach an adequate trade-off between the number

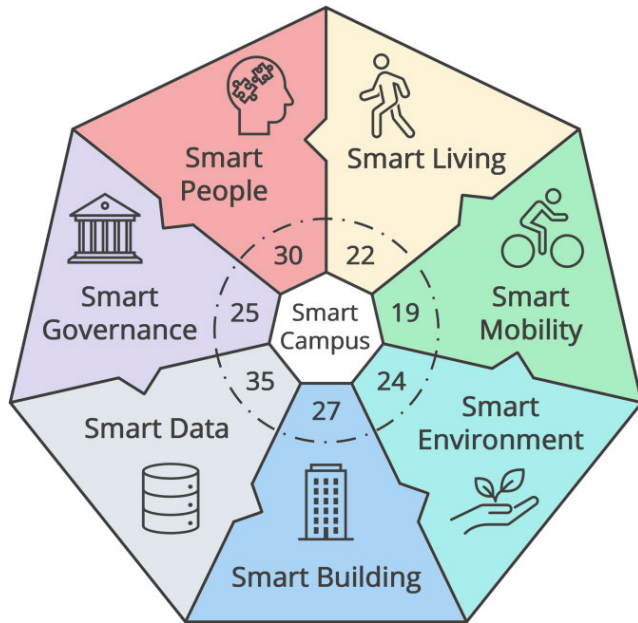


FIGURE 5. Non-exclusive categories used in the present review for encompassing the concept of smart campus.

of subsections and the coherence of the papers in a given subsection. The result of this review is displayed in the following sections, one category at a time, with a common structure. First, the relevant recurring terms in titles and abstracts are shown using a cloud of terms [18], and a figure representing findings in publication is presented. The font size of a word in the clouds indicates its recurrence in the titles and abstracts. We then explain how the smartness of a campus can improve its sustainability, and a summary of the literature completes the section. According to Farley and Smith [19], the concept of sustainability is so broad and overly used that it has somewhat lost its meaning. Sustainability concerns three life aspects, often organized as pillars, a Venn diagram or nested spheres: ecological environment, society, and economy as the smaller sphere. The sustainable aspects chosen for each category represent actions or values found in the articles that pursue a long-term perspective regarding the three spheres.

III. SMART BUILDING

Buildings are not only a major asset of campuses, but account for nearly 40% of energy consumption and emissions in developed countries [20]. Smart, sustainable and responsible use of building resources can therefore lead to substantial reductions in energy and environmental footprints during construction, use, and end of life phases. Although many definitions have been proposed over the years, smart buildings usually distinguish themselves by their high interactivity and connectivity, their sustainability, and their energy and comfort performance. They collect and analyze large amounts of data in real-time, and can adapt accordingly [12]. Smart building technologies populate a wide spectrum regarding the level of control. Some of the more passive and less intrusive

approaches involve basic user advisory input (e.g., visual monitors, conveyance of data, advisory notifications, alerts, etc.). At the other end of this spectrum lie fully integrated, proactive and autonomous building technologies (such as artificial intelligence systems involving IoT and machine learning, integrated energy demand management/response, transactive building controls, etc.). Hybrid approaches are also quite common and effective (e.g., smart thermostats capable of operating in either manual or automated modes). As we move towards smarter and greener campuses, a significant effort is being devoted to enhance the overall performance of campus building stocks.

Figure 6a shows the relevant recurring terms in titles and abstracts with the size of a word directly linked to its occurrence. Figure 6b illustrates the main aspects treated in the publications related to smart buildings. Numbers in brackets in the figure point to the references reported at the end of the paper that cover a specific aspect. Note that the publications focusing on on-site electricity production were included in Section IV.

In Fig. 6b, “physical” topics like windows and sensors are represented on the left side, while “platform” topics like control and mobile application are on the right. The high number of studies concerning Heating, Ventilation, and Air Conditioning (HVAC) in smart campus buildings can be attributed to its importance on occupant comfort, energy consumption and costs. In particular, more than 40% of building energy use can be attributed to HVAC systems, generally [21]. Thus it is not uncommon for HVAC energy consumption to hold the unique position of using the largest share within buildings, which themselves often use the largest share among all major demand sectors [22]. Naturally, this implies a commensurate impact on facility costs, including fixed assets such as heating and cooling systems, and variable costs such as electricity, natural gas, water, and other operating, labor and maintenance expenses. Smart thermostats and associated IoT control algorithms are today one of the most recognizable smart devices available to the general public and are therefore being more widely deployed on campuses as well. This is for good reasons, as they are mobile device enabled, and can maintain or improve comfort, reduce utility bills, while contributing to reductions of up to 10% or even 20% in energy consumption [23], [24].

Figure 7 shows the sustainability aspects that the publications touched on. Since buildings and construction are responsible for over one-third of global energy consumption [25], it is not surprising to see a substantial number of actions to improve building energy efficiency. For example, Amaral *et al.* [13] reviewed the sustainability actions and initiatives of university campuses, and the reduction of building energy consumption is one of the most popular initiatives. Also, these authors recommend that an integrated framework be established to facilitate the dissemination and monitoring of the results of these initiatives. Increasing renewable energy sources and reducing carbon footprint are not frequent in Fig. 7 since power production is included in Section IV.

level and medium intelligence level, but offered the most flexibility in terms of energy consumption. Laboratory had a high importance level, but no flexibility.

Chalfoun [27] described the efforts of University of Arizona (USA) to reduce energy consumption of its campus' buildings. Level III energy audits were conducted by students and faculty members to identify energy saving opportunities. The current energy intensity of the nine buildings investigated was 221 kWh/m². Proposed solutions focused on windows, external insulation, shading system, energy-efficient light fixtures and envelope solar reflectance. As for HVAC systems, changes in set-points, replacement of old components and collecting condensates for landscape use were proposed. No implementation of these solutions was described in the paper though.

Escobedo *et al.* [28] analyzed the energy consumption and greenhouse gases (GHG) emissions of the buildings of the main campus of the National Autonomous University of Mexico (Mexico). Based on energy audits, it was found that lighting required 28% of the energy consumed by the campus, followed by research equipment (17%), refrigeration (14%) and pool heating (9%). The authors analyzed scenarios that could reduce energy consumption, the base annual energy intensity being 82.7 kWh/m²y.

The smart campus project at University of Brescia (Italy) was organized in phases and relied on three pillars: envelope refurbishment, improvement of building services efficiency, and smart control. De Angelis *et al.* [29] described simulations to assess savings from envelope renovation and renewable energy production. The maximum energy reduction achieved 37.3% by improving thermal properties of the envelope, a better control of the solar gains and enhanced ventilation. With a base energy intensity of 104.7 kWh/m²·y, each renovation strategy changed the energy intensity to values from 97.3 (addition of shading blades) to 65.6 kWh/m²·y (enhanced ventilation). It was further estimated that PV could provide around 75% of the energy needs.

Chung and Rhee [30] performed an on-site survey to determine the energy consumption patterns of existing university buildings on a South Korean campus. The current annual energy intensity varied between 106 and 399 kWh/m². The authors proposed a methodology to evaluate the impact of different energy-saving strategies based on simulations. They adapted the strategies to the type of building, considering schemes such as installing automatic standby power cut-off switches and changing the U-value of the envelope, the set-point temperatures, the windows and the lighting system. The potential to reduce energy consumption varied between 6 and 29% depending on the building.

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an optimization tool to support decisions in order to minimize CO₂ emissions. Stadler *et al.* [31] introduced building retrofit measures into DER-CAM and demonstrated the use of this new tool for an Austrian campus building. Given the current energy and building improvement costs, it was found that the average U-value of the

envelope should be increased by 20% compared to the current value.

Mehta *et al.* [32] developed a 3D virtual version of the buildings of the Nanyang Technological University (Singapore) campus to simulate the use of different technologies and to optimize building performance. This work was part of the EcoCampus initiative, which aimed at reducing the energy, water and waste intensity by 35% in 2020 (baseline 2011).

B. BIG DATA PLATFORMS AND FRAMEWORKS

As campuses install more and more sensors into buildings, a need emerges to properly organize data collection and information flow. Different big data platforms have been developed and tested in campuses.

Moreno *et al.* [33] illustrated the foundations of big data techniques applied to the smart campus of University of Murcia. After introducing an IoT-based architecture, they addressed three different building-related problems: indoor localization, building energy consumption prediction and comfort/energy saving through optimization.

Bates and Friday [34] offered lessons learned in the development of a platform to make the Lancaster University campus smarter. In particular, the case study is oriented around the integration of data from the energy and building management system (EMS and BMS) to facilitate analysis and optimization. The authors described several opportunities brought by the system (such as providing a strategic oversight, optimizing heating system, conducting live experiment, etc.), as well as a series of challenges (such as data granularity, complexity and missing metadata, system age, security and understanding the meaning behind the data).

Corotinschi and Găitan [35] designed a solution to manage the electricity and heating systems of 11 university buildings. The purpose of the project was to design a smart platform for the efficient management of heating and electricity systems in each room and common areas of each building. The platform included an IoT gateway for each building, a big data centre, a Supervisory Control And Data Acquisition (SCADA) system and an analysis center.

C. INTEGRATION OF REAL-TIME DATA COLLECTION INTO BIM ENVIRONMENT

BIM (Building Information Management) is defined either as a process for the virtual design, construction and operation of a building or as a 3D detailed model of buildings that acts as a virtual twin. BIM emerged in the last decade as a cost-effective way to coordinate the stakeholders with a single model during the planning, design, construction and operation of buildings. Authors have thus aimed to couple BIM models with real-time data collected from building sensors, in particular for the sake of data visualization.

Dave *et al.* [36] presented a platform implemented in Aalto University (Finland) that integrates the built environment data from IoT sensors in a campus web-based system that can provide information about energy usage. Occupancy and user

comfort can be assessed through open messaging standards. A BIM model is used to manage the relationship between spaces and IoT data for visualization. Different dimensions are considered: 1D (live and historical sensor data), 2D view (floorplan map), 3D view (locating sensor and 360 images).

Chang *et al.* [37] represented IoT sensor information in a Taiwanese university campus BIM model. Such visualisation platform can support decision-making processes. The authors described a test case in which thermal comfort can be automatically visualized in classrooms.

Desogus *et al.* [38] defined a “cognitive building” as a building that is able to extract knowledge from users’ feedback and translate it into functional intelligence. The concept was first applied to a laboratory building at the University of Brescia, and then, to a pavilion at the University of Cagliari, both in Italy. In the first case study, sensors data and BIM model were linked, facilitating visualization, model calibration and sense-making. In the second case, sensors were installed to measure air temperature, relative humidity, illuminance, window opening, CO₂ indoor production, user presence and electrical consumption. The multi-sensor room controller sends this information through Wi-Fi connection using an access point/router connected to the university network via LAN. For the same building at University of Brescia, Ciribini *et al.* [39] presented the use of real-time sensor measurement from the BMS into a BIM environment. This facilitates the visualization of the data. An application has been developed to allow access to the data and to provide feedback of the students on comfort levels.

D. ARTIFICIAL INTELLIGENCE FOR PATTERN RECOGNITION, FAULT DETECTION AND CONTROL

Artificial intelligence (AI) aims at deploying “smartness” without human intervention. Machine learning and artificial neural networks can be employed to understand and predict building behavior, find anomalies and act accordingly.

Five clustering techniques are used by Panapakidis *et al.* [40] to investigate the electricity consumption profile of the Aristotle University of Thessaloniki (Greece). The generated clusters reduce the dimensionality of the dataset and their analysis can help to identify possible opportunities for energy efficiency improvements.

Weng *et al.* [41] introduced an unsupervised anomaly detection method, based on long short-term memory networks and autoencoder neural networks. The objective of that work was to identify energy consumption anomalies in a smart campus, where their hidden patterns in the data are usually unknown.

Miller *et al.* [42] developed a method to identify infrequent daily patterns into building data, with the idea of detecting faults and potential energy saving opportunities. The approach was applied to the chilled water plant of a campus in Singapore for which an extensive dataset was available. Results showed 39 anomalous days in the dataset, which was consistent with faults observed on site.

Gupta *et al.* [43] compared a pattern recognition adaptive controller and model predictive controller for HVAC systems. One of the air handling units at the Texas Tech University campus was used for testing these advanced control methods, which proved to be more effective than the traditional controller.

Within a smart campus project, Pombeiro *et al.* [44] compared linear regressions, fuzzy modeling and artificial neural networks to predict electricity consumption of a building, based on predictors such as time of day, weather and occupancy. The two former methods provided better accuracy than linear regressions.

In Ref. [45], Domínguez *et al.* presented a three-layer power monitoring system that was developed for the buildings of the University of León (Spain). In the client layer, data can be exploited to find electricity consumption patterns, detect faults and predict future demand. The authors used a self-organized map (SOM) approach to visualize the electric variables. The different building energy consumption patterns were compared based on dimensionality reduction and clustering techniques. Cost savings of 15% were realized by adjusting the energy contracts to better match the actual electricity consumption.

E. ROLE OF OCCUPANTS

Literature reveals the importance that occupants (students, staff, etc.) have on the building performance and in particular on its energy consumption. A smart building would not only be aware of the present and future presence of people, their actions and behaviors and their level of comfort, but would also adapt accordingly. This implies the development of bi-directional communication strategies between buildings and occupants. Developing a better understanding of occupant behavior in campus buildings is addressed in literature.

Ganji *et al.* [46] studied the real usage of a dense wireless local area network or WLAN (users’ behavior and mobility patterns) in the campus of the Politecnico di Torino (Italy) to evaluate the energy saving potential of introducing access point (AP) on/off switching strategies. Because users’ patterns are repetitive and due to the significant differences between days/nights and weekdays/weekends, savings of up to 40% can be achieved thanks to the implementation of this strategy.

In University of New South Wales (Australia), Sutjarittham *et al.* [47] proposed a beam-counter based system to measure attendance and developed an optimization algorithm for allocating courses to rooms based on the collected data. The method was tested in 9 real classrooms over a period of 12 weeks, showing that using attendance rather than enrollments results in potential savings of 52% in room cost. The authors [48] then compared three machine learning algorithms to predict classroom attendance which fed into their optimization algorithm, resulting in over 10% savings in room costs with very low risk of room overflows.

The following works mentioned in this section are related to buildings of the University of Brescia, in Italy. One often

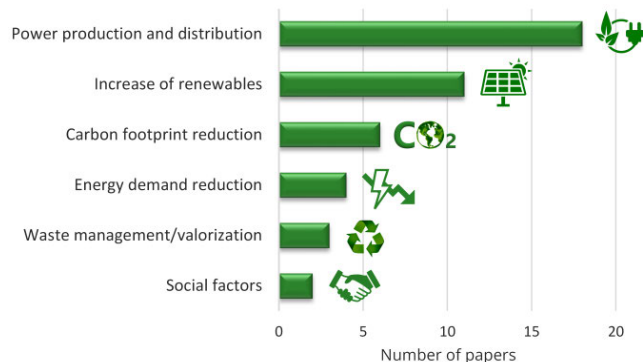


FIGURE 9. Sustainability facets found in the publications of the smart environment category.

of both thermal and electrical production/load [53]. Campus microgrids have often been used as case studies to demonstrate how to make energy systems smarter (using energy system optimization models to define the operating strategy) and evaluate the cost and environmental benefits that can be achieved with this approach.

According to Balac *et al.* [54], the University of California, San Diego (USA) “is the owner-operator of a 45 MW peak load Smart Grid and one of the first adopters of many new technologies, including multiple renewable and non-renewable energy generation resources, significant energy storage, and sophisticated monitoring”. The authors introduced an engine employing time series prediction algorithms to improve the efficiency of this smart microgrid, while reducing its cost and carbon footprint.

Bracco *et al.* [55] formulated an optimization model for the design of a smart energy infrastructure integrating PVs, electricity storage, loads and electric mobility. Their case study is the Savona Campus – University of Genoa (Italy) and one of the focuses of their work is the role of electric vehicles (EVs). Their solution allowed reducing both operating costs and annual CO₂ emissions. The storage system of this system is studied in [56], where EVs are deemed suitable to absorb the energy surplus during the day and level the load (see Section V-D). The Smart Polygeneration Microgrid (SPM) of Savona Campus operates as a test-bed facility for the research and development of smart grid components. According to Bracco and Delfino [57], microturbines are becoming more popular in smart microgrids such as those found on campuses, since they can provide both heat and electricity. The authors developed a model to simulate one of the three micro gas turbines installed within the SPM of Savona Campus. This microgrid system supplies the campus with both heat and electricity; it includes PVs, wind turbines, concentrating solar power Stirling engines, micro gas turbines, gas boilers, an absorption chiller and batteries [58].

Gambarotta *et al.* [59] developed a library of models to simulate each component of a smart energy system that includes several sources of energy. The authors built a dynamic energy model of the heating and cooling network of the campus of University of Parma (Italy) and were able to

optimize its management strategy through simulation, reducing by 1.5% the consumption of primary energy.

Lazaroiu *et al.* [60], [61] optimized the operation of a smart campus on the electricity market for maximizing its overall profit. The smart campus includes a heat and power plant and renewable energy sources. The authors mention that the energy production and consumption data they used are real data covering one year (2013-2014).

Makatji and Ntsaluba [62] studied how to reduce the environmental footprint of the energy supply to a campus, by relying on renewable energy sources and energy storage. The case study was the Auckland Park campus of the University of Johannesburg (South Africa) and the authors demonstrated the possibility of satisfying campus needs with an off-grid system relying on PVs, biogas produced mainly from food waste, and battery storage.

McLarty *et al.* [63] used the microgrid of University of California-Irvine (USA) as a case study. This campus had 1 MW of solar power in 2014, and was serviced with seven chillers, a 13.5 MW gas turbine, a 4.5 steam turbine generator and a 175 MWh cold-water storage tank. They optimized the dispatch of a multi-chiller plant with cold water thermal storage with a predictive controller, and showed that utility bill costs can be reduced by 12%.

Mišák *et al.* [64] investigated active demand side management (ADSM) in off-grid systems, and they tested their approach on a platform developed at VSB – Technical University of Ostrava campus (Czech Republic). Based on fuzzy forecasting and multilayer neural network, the proposed ADSM algorithm increases the efficiency and reliability of the renewable energy sources with intelligent scheduling.

According to Talei *et al.* [65], [66], a good example of microgrid is a smart campus. Campus microgrids can be seen as a smaller version of a smart grid, which is often coupled to heating and cooling infrastructures. Their size and availability facilitates their analysis, modeling and testing. In [65], the authors introduce examples of smart campus microgrids and the experience of Al Akhawayn University (Morocco), where measures of delay in information transmission are presented. In [66], they describe the main components of such a microgrid, and in particular, the energy management system (EMS), its different architectures and the value-added of cloud computing in this context.

As a notable contribution outside of the present literature review, Hetterich *et al.* [67] introduced an open source linear programming optimization model (<https://github.com/tum-ens/urbs>) for the design and optimization of smart energy grids including heating, cooling and power infrastructure. The Campus Garching of the Technical University of Munich (Germany) served as a test bed for the model and demonstrates that the use of such optimization allows achieving simultaneous cost and CO₂ emissions reductions.

B. CAMPUS-SCALE SUSTAINABILITY INITIATIVES

Many universities have engaged in comprehensive sustainability action plans that include some smartness features.

The level of success of the low carbon transition path of the campus of University of Palermo (Italy) was studied by Guerrieri *et al.* [68]. The energy data of 18 buildings of the campus are presented and the actions undertaken from 2010 regarding buildings, street lighting and mobility are introduced, and their impact analyzed with the method proposed by Yoshida *et al.* [69]. Then, the authors analyzed the transferability of this method to cities and found that it can be adopted to assess the effectiveness of energy policy, waste management, and public transportation.

Ho *et al.* [70] demonstrated their formulation of a decision-making model for energy conservation and renewable energy for the campus of Chaoyang University of Technology (Taiwan). The objectives were the return on investment, usage of renewable energy, and investment costs. Based on the solutions, different alternative low carbon campus solutions are shown, including the installation of PVs, solar thermal panels, and rooftop garden.

Leite *et al.* [71] demonstrated how to reduce the power consumption of battery-dependant devices in a smart campus through proper prioritization of messages, balancing network emergency traffic, and fuzzy control.

Ravesteyn *et al.* [72] noted that many sustainability initiatives in the higher educational environment seem disconnected from an overall vision and strategy. They interviewed experts and developed the concept of smart green campuses. Supported by IT, new models of learning, smart sharing of resources and better usage of buildings and transport characterize this concept. Recalde *et al.* [16] presented a transition framework to prepare Ecuadorian universities for the concept of smart campus. Among others, the authors identified the appropriate strategies to maximize asset lifecycle and optimize energy usage, recognizing their impacts on each field of the smart campus. Through the case study to transform the Escuela Superior Politécnica del Litoral (Ecuador), it was found that adequate actions are the deployment of LED lighting systems and PV panels.

C. WASTE MANAGEMENT AND RECYCLING

Reducing the amount of waste produced on a campus and improving its management is an important aspect of sustainable and smart campuses.

The University of Monastir (Tunisia) has an initiative oriented on circular economy and sustainable waste management in the campus area. Bentoufa *et al.* [73] reported different projects that are conducted such as valorization of waste, public art, development of environmentally-friendly products and of solar heating systems made from used soft drink cans. They emphasize that testing ideas in the framework of a smart campus is a useful step before moving to the smart city scale.

Pagliari *et al.* [74] applied a framework introduced earlier in literature for finding the most suitable environmental strategies to transform Sapienza campus, University of Rome (Italy), into a smart campus. The waste collection and recycling system of the campus was then simulated,

including different potential improvements like compactors and replacements of garbage truck in order to evaluate their energy, economic and environmental benefits.

Ward and Gittens [75] proposed relying on the functional capabilities and sensors of retired cell phones to develop smart campus applications. They introduced models to identify the attributes/sensors of the cell phone and its repurposing possibilities.

D. CAMPUS ENVIRONMENTAL MONITORING

The development of sensors and monitoring strategies is intricately related to the smart campus concept, thus measuring environmental and energy features on campus has been investigated by different researchers.

A system for monitoring outdoor air quality (i.e., concentration of CO₂, CO, NH₃, and O₂) on campuses with a wireless sensor network is described by Muladi *et al.* [76]. The system uses the MQTT protocol to facilitate transmission from sensor nodes to brokers via the wireless local area network. Air quality data is then reported in real time via a web server. The approach was tested at Universitas Negeri Malang (Indonesia).

Okeniyi *et al.* [77] presented data on energy generation costs from distributed gas-fired turbines and diesel-powered systems at the smart campus of Covenant University (Nigeria). These data can be employed for the planning of new power plants and of combinations of energy generation systems in a smart university campus.

Liu *et al.* [78] proposed collecting electricity usage data in campus buildings and processed this big data with cloud computing in order to build a real-time energy monitoring system for smart campus. The system was implemented at Tunghai University (Taiwan). In the same university, Chang *et al.* [79] designed and implemented a real-time electricity load monitoring platform. This high-performance data processing environment performs the storage and management of the data from the smart meters and long-term historical data, and allows analyzing electricity consumption.

V. SMART MOBILITY

Smart mobility means using modes of transportation in a cleaner, safer and more efficient way. In the context of a smart campus, mobility is a key element to make on campus stay more enjoyable for students, staff and visitors. The relevant recurring terms in titles and abstracts are shown in the cloud of terms of Fig. 10a. Figure 10b shows the mode of transportation studied in publications by binary count (numbers in brackets point to the references at the end of the paper). Of the relatively few papers in this category, half of them are on cars/motorcycles while only one study was found to encourage the use of bicycles. Surprisingly, no papers mentioned hydrogen to ensure a buffer between electricity production and vehicle charging, as renewable energy often leads to a fluctuant production. For example, the collaborative laboratory “eCAMPUS” of University of Lille (France) and Université du Québec à Trois-Rivières (Canada) analyses

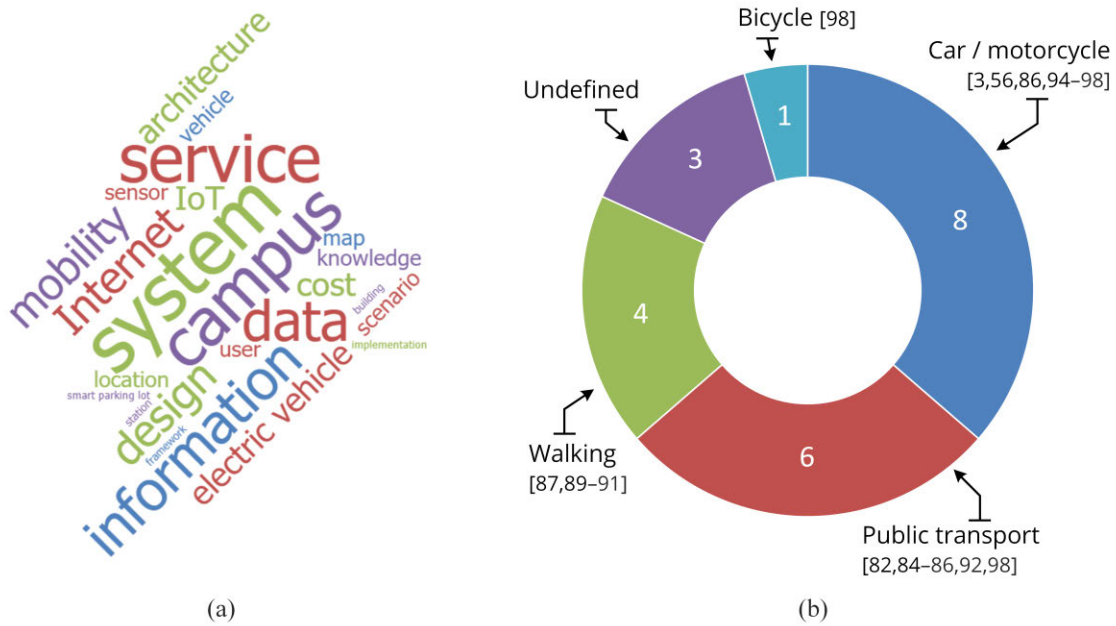


FIGURE 10. Results for the smart mobility category: (a) Cloud of terms in titles and abstracts (three or more occurrences); (b) Modes of transportation covered by the articles.

methods for reducing the ecological footprint of university campuses using more electrified vehicles, where hydrogen can be used directly for fuel-cell vehicles or as an energy storage solution [80].

Figure 11 displays the sustainability aspects present in the papers. They mainly revolve around the societal sphere by making the mobility experience in the campus more pleasant, contributing to a higher quality of life. Only three publications propose smart accommodations for people with disabilities. Actions concerning the environmental sphere of sustainability are found, namely on the optimization of the power distribution to vehicles, reduction of the GHG produced and fostering the use of renewable power sources. One could argue that smart initiatives on car parking are sustainable only if they can lead to the reduction of the parking space. The economy sphere is covered only with local economy on exchanging power in EVs charging stations.

Papers have been categorized in five topics, corresponding to subsections V-A to V-E: (a) monitoring and understanding mobility on campuses, (b) bus transportation, (c) assistance and navigation on the campus site, (d) electrical vehicle charging, and (e) car parking.

A. MONITORING AND UNDERSTANDING MOBILITY ON CAMPUSES

Developing a better understanding and monitoring capacity of how, where and when people move on a campus allows improving current infrastructures, scheduling, and service offering.

Toutouh *et al.* [81] focused on the development of a cyber-physical system for understanding mobility, with an

application to the smart campus initiative at the University of Malaga (Spain). The system captures road-traffic information, where a data subset is found through optimization to accurately describe the whole dataset, revealing mobility patterns and predicting road traffic flow. The technique couples evolutionary algorithm and machine learning to reduce the required data significantly.

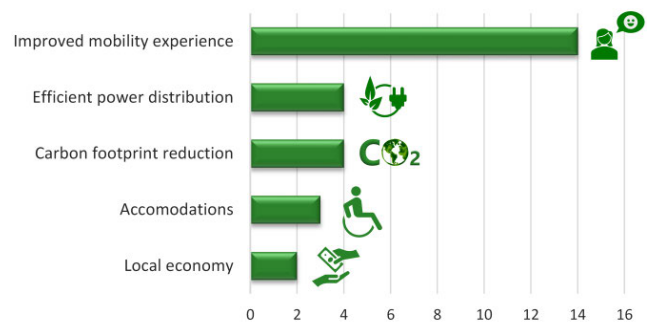


FIGURE 11. Sustainability facets found in the publications of the smart mobility category.

Somsuphprungyos *et al.* [82] employed student enrolment data, visualization of headcount in the buildings and student movement to feed their smart system that makes recommendations regarding bus shuttle services and routes. The chosen ontology tool allowed representing the relevant concepts on campus including building, people and things for defining semantic relations among them.

Li *et al.* [83] proposed a multi-access edge computing (formally mobile edge computing, henceforth named MEC)

platform to provide, among other things, data acquisition for four applications on the campus of Beijing University of Posts and Telecommunications: i) association of buildings by analyzing everybody's location regularly; ii) dwell time distribution to build a statistical model; iii) trajectory prediction using the Markov chain and points of interest; iv) analysis of people flow to identify abnormal behavior of a crowd and help in school planning.

B. BUS TRANSPORTATION

Many universities have a bus shuttle system circulating on their campus. Authors studied how "smartness" could help improve the service offered by these buses.

Feng *et al.* [84] designed an intelligent bus positioning system for a smart campus and introduced touch screens at bus stops to count the number of waiting passengers. Then they optimized bus scheduling based on the information collected from the system to maximize passengers' and bus companies' satisfaction. The mathematical model was tested in a numerical simulation and has not yet been implemented on a campus.

Pattanusorn and Nilkhamhang [85] presented a real-time bus monitoring system for universities that rely on existing Wi-Fi infrastructure to reduce costs. To estimate bus positions in "dead zones" where Wi-Fi signal is not good on the campus, the model can also predict bus travel time with historical data. This prediction model was found satisfactory after it was tested using historical data of bus travel information of Thammasart University (Thailand) collected over the space of one year.

Using instances of actual data from Walailak University (Thailand) into the test case scenario, the shuttle bus management system recommended in Ref. [82] calculates the number of service shuttle buses and their route based on student movement. Similarly, Sutjarittham *et al.* [86] reported that the University of New South Wales (Australia) has started measuring the queues at bus stops with miniature ultrasonic sensors and connections count of campus Wi-Fi access-points. They plan to add a method that involves users contributing data, where a person joining the queue can scan the QR code nearest them with their mobile phone.

C. ASSISTANCE AND NAVIGATION ON THE CAMPUS SITE

Smart campuses can exchange information with students, staff and visitors for navigation or assistance purposes within the campus, which often takes the shape of mobile applications.

To facilitate spatial orientation, an indoor positioning system and an outdoor positioning system were combined by Torres-Sospedra *et al.* [87]. Two mobile applications were developed at Universitat Jaume I (Spain), one providing access to map-based information about the facilities of the campus, and another one allowing users to interact with the campus through augmented reality.

Arsan *et al.* [88] proposed an Android app for mobile to help visitors navigate easily around the campus of Kadir Has

University (Turkey) employing beacon infrastructure. Using path loss model and trilateration for localization, the system provides users with a 3D map, an augmented reality, and directions to the daily events that take place. On the campus of Feng Chia University (Taiwan), Chen *et al.* [89] described the implantation of an IoT-enabled system that provides indoor and outdoor guiding within the campus to quickly reach places and find students. Based on deep learning-based face recognition, it could efficiently reduce the time to find a target student who needs care on campus.

Petrova and Tabunshchik [90] proposed a smart campus mobile application with an indoor navigation system for persons with disabilities, helping them to find a location, build the necessary route and interact with the campus systems in Zaporizhia National Technical University (Ukraine). The prototype of a smartwatch has been developed by Kim *et al.* [91] at Toyo University (Japan) to help students with disabilities in their daily life on campus. The smartwatch operating in an IoT environment can enhance the accessibility to physical spaces and equipment by controlling in-building devices.

At CETYS University (Mexico), an initiative of autonomous vehicles traveling between buildings is presented by Basaca-Preciado *et al.* [92]. The approach based on IoT utilizes several sensors to map the environment and plan the trajectory of the solar powered vehicles without human intervention. Such transport medium is meant to benefit and assure the security of people with mobility or visual impairment for the transit between classes, and of elderly population during periods of high temperatures.

D. ELECTRIC VEHICLE CHARGING

There are more and more electric vehicles (EVs) on the roads (increase of 63% in 2018 from the previous year, the global stock exceeded 5 million [93]), thanks to the growing environmental concern of the population and decline in prices. As a result, many campuses have integrated charging stations. This offers interesting opportunities for optimizing the charging scheduling and exchanges with the grid.

A framework for local energy trading between EVs and a smart parking lot was designed by Ahmed and Kim [94]. A smart management of the electricity flow between vehicles and the grid can help reduce peak demand and thus generate savings that can be shared between the parking lot manager and car owners. In another study, the same group studied communications between electric vehicles in charging stations and the parking lot local controller [95]. In 2019, the authors designed a system relying on IoT to manage electric vehicle charging at a university campus [96]. The test case was a smart parking lot in the same campus.

Brenna *et al.* [56] investigated the potential role of EVs to replace or improve energy storage systems in a smart microgrid. They considered the Savona Campus of the Genoa University (Italy) as a test case and attempted to reduce the cost of the overall smart campus grid infrastructure considering the energy potential storage of EV batteries.

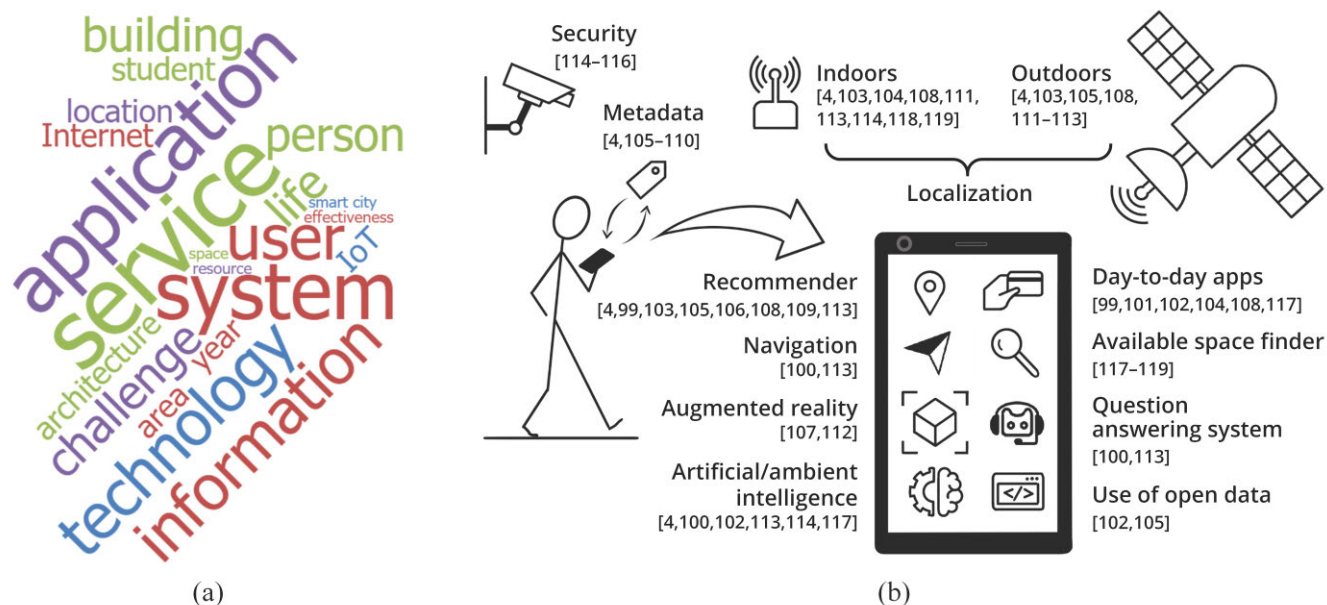


FIGURE 12. Results for the smart living category: (a) Cloud of terms in titles and abstracts (three or more occurrences); (b) Distribution of aspects covered in publications.

E. CAR PARKING

Most campuses have parking spaces for staff and students' cars. From the point of view of the car owner, finding a free space can be problematic, leading to waste of time and fuel. On the other hand, parking lot managers want to achieve high occupation rates and develop a better understanding of how and when the spaces are used. In order to address these issues, the concept of "smart parking" emerged, in which parking lot users and owners exchange real-time information and data to facilitate optimal decision-making.

A low-cost sensor for monitoring the usage of a parking space was developed by Bandara *et al.* [3], combining magnetic and distance sensors. A server receives and treats the information collected from the sensors and feeds a mobile application that displays the available spots on a map to the subscribers. Similarly, Sofwan *et al.* [97] introduced a system to detect the availability of outdoor parking spaces by detecting moving vehicles (entering or leaving). The deployed system, based on a background subtraction method, presented an average accuracy performance that exceeds 92.60%.

According to Sutjarittham *et al.* [86], the IoT technologies can benefit various stakeholders (students, staff, etc.). Of the two reported examples of IoT deployment that relate to smart mobility, one is for understanding and managing parking lot occupancy. Profiling real-time usage enables the estate management to plan for the number of bays they can rent to car sharing service providers.

Planning of the implementation of intelligent transportation in the construction of a smart campus is discussed by Tang and Chen [98]. A service of barrier gate based on campus card is proposed to monitor entrances and departures

from campus grounds, as well as a parking guidance service in the form of a digital map that gives the current position of the driver and the empty parking area on the campus.

VI. SMART LIVING

This section gathers publications related to making "smarter" the everyday aspects of studying, working or living in a university campus. Figure 12a shows the cloud of terms from titles and abstracts, where the accent is on applications and services to benefit the users, and Fig. 12b illustrates the principal aspects treated in the body of work analyzed. Numbers in brackets in the figure point to the references reported at the end of the paper that covers a specific aspect.

What stood out in the publications is the need to use smartness to make relevant information more accessible. Curiously, no paper was found on food-related topics (e.g., making canteens smarter), and only a few on services related to on-campus lodging. The accent is on recommending personalized services, mining users' data and offering indoor and outdoor localization service. In Fig. 12b, day-to-day applications include payment, meeting planning, communication services, and so on.

Regarding the sustainability aspects reported in Fig. 13, the environmental sphere is somewhat left behind in favor of the societal sphere, focusing on making life easier, helping save time and giving useful information without burying the users under distracting notifications (hence the importance of personalization). AI and AmI (ambient intelligence) are key approaches to understand users' behavior based on their metadata and respond accordingly without human intervention.

Papers have been grouped into 4 topics, corresponding to subsections VI-A to IV-D: (a) applications for intelligent services, (b) data mining for personalized experience and services recommendation, (c) surveillance, localization and navigation systems, and (d) real-time space use.

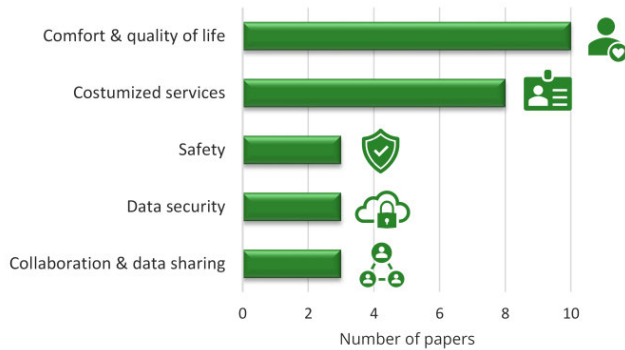


FIGURE 13. Sustainability facets related in articles of the smart living category.

A. APPLICATIONS FOR INTELLIGENT SERVICES

Several applications and platforms have been proposed in the last decade to make life easier on campus. Some provide intelligent services that facilitate day-to-day tasks and others use context-awareness, i.e., a computing ability of mobile devices that gather information on its user and environment to act accordingly, most of the time depending on the location.

Adamkó *et al.* [99] described a cloud-based system to ease the everyday tasks and communication between students and instructors in a university environment. The application includes chat rooms based on the course name, attendance status, consulting appointment interface for instructors, and a chat bot capable of answering predefined questions. Similarly, Gaglio *et al.* [100] presented a virtual assistant to help students and staff to move around a campus (locating points of interest) and to answer common questions. The assistant answered 75% of the questions correctly in the performed evaluation, the authors highlighting the positive impact of training the system.

Considering the queuing problem for paying on university campuses, Li *et al.* [101] proposed SafeMP, a mobile payment system employing mechanical wave transmission with an accuracy of 97%. It employs linear resonant actuators (LRA) (used in most mobile phones today) where mechanical waves are generated by moving a metallic mass around a neutral position. The authors describe a novel compensation method that addresses the signal attenuation, and an algorithm for separating the aliasing bits in the same time slot.

Based on an existing IoT device management platform, Lin *et al.* [102] created DormTalk, an edge IoT computing platform for several dormitory applications, including smart socket, washing machines, dryers, ACs, indoor aquarium and plant box. The modularised IoT devices and applications can be reused through a graphical user interface, where students

with or without programming ability can create new IoT applications.

Petcovici and Stroulia [103] presented their framework for location-based services (LBS) constituted of an Android application that can be put in a passive state for minimizing energy consumption, and web applications for users and managers. Using infrastructure typically available in smart campus environments, the framework relies on indoor-outdoor localization to specify the available services in proximity. Also using LBS, a meeting room booking management application was proposed by Rusli and Halim [104], integrating the concept of a location-based smart notification system. Aware of the frequent interruptions often experienced by users on mobile application, the authors argue that their smart notification feature can minimize substantially the possibility of such overload.

B. DATA MINING FOR PERSONALIZED EXPERIENCE AND SERVICES RECOMMENDATION

To improve user experience and recommend services, the user's context data such as its location, the time, the device and nearby devices are of great value. The collection of such data allows the smart campus to establish patterns and continually adapt to the user's behavior, leading to an enhanced personalization of the services that facilitate day-to-day life. However, it requires frequent updates of privacy protection policies.

In [105], Adamkó *et al.* proposed a web service interface containing a personal calendar, a meeting planning module and an ontology-based recommender system. The users receive notifications based on their preference and meta-information. The system has an extensible and open interface allowing people to generate new content and services. De Paola *et al.* [4] suggested a method to detect the points of interest visited by users of a campus, by using mobility tracers collected through smartphones. The authors argue that understanding users' habits is required to develop advanced services, such as personalized recommendations and virtual assistance. Manqele *et al.* [106] proposed using content-based algorithm to select relevant services and manipulate their description based on user context and user preference. Results of an application scenario show that it is more effective than collaborative filtering technique.

Liu *et al.* [107] described a platform they built based on MEC for users' semantic information analysis (people flow, trajectory prediction, etc.). It also comprises an augmented reality mobile application and a smart class application. MEC presents low latency and high bandwidth compared to traditional mobile cloud computing.

Bello and Jiménez-Guarín [108] developed a platform called CAPELA which provides users with information and recommendations based on their indoor or outdoor location, profile, interests and behavior. The system builds on different sources of information with different formats. Sun *et al.* [109] described the smart campus systems of the University of Science and Technology of China in which behavioral data

analysis is exploited to offer services to students in their daily lives. Sources of information can include E-card data (used for identification and consumption), course teaching system, email system, campus security monitoring, financial system, etc. Life-style reports can be provided to students, as well as recommendations (friends, books, places of interest, etc.).

Inspired by “brain traffic” techniques, Seidita and Chella [110] presented an approach for analyzing the behavior and emergent needs of citizens in a smart city to provide useful intelligent services. Using brain metaphor and agent-based modeling techniques to represent intelligent social phenomena, the created model was applied to a smart university campus as an experiment. Examples of said services are outside the scope of the paper.

C. SURVEILLANCE, LOCALIZATION AND NAVIGATION SYSTEMS

Knowing the position of the users for context-aware services requires indoor and outdoor localization techniques (e.g., beacons and GPS). It is also mandatory for offering navigation services and can enhance security on the campus. While overlapping the themes of subsection B, the present subsection gathers papers where localization and surveillance are not specifically used for personalization services.

Bonafini *et al.* [111] proposed equipping a LoRaWAN node with both GPS and Ultra Wide Band-based real-time location systems for providing indoor and outdoor position in smart campus applications. The measured location errors were of the order of a few tens of meters outdoors and a few tens of centimeters indoors. Özcan *et al.* [112] developed a prototype of augmented reality application for the Muğla SıtkıKoçman University Campus (Turkey). Based on GPS information and a picture taken by the user, the application processes the image, detects the user’s location and adds information into the picture image. External data sources such as Twitter data could eventually serve to provide information to be added.

Chaouche *et al.* [113] introduced a predictive technique in the context of a smart campus to offer spatial guidance services, based on contextual information such as spatial location and dynamic neighborhood. The system uses a higher-order agent architecture (HoA) and graphical user interface to interact with a user.

To report incidents occurring on the campus faster, Liu *et al.* [114] developed a mobile application that lets users send alerts with their real-time location to the university police department. Employing a hybrid system combining Wi-Fi fingerprinting with Bluetooth beacon-based trilateration improved the accuracy and stability of the localization system.

Gahlaut and Seeja [115] created an IoT surveillance system for the Indira Gandhi Delhi Technical University for Women, that captures and records videos which can be sent through the mobile network. The system proved to be more reliable and secure than the existing system. Kwon *et al.* [116] developed a gate security system

combining ID card, face recognition, and role-based access control modules to strengthen security on smart campuses. The created testbed uses containerization, deemed to have a higher performance and scalability than virtual machines.

D. REAL-TIME SPACE USE

Measuring real-time space use in campus rooms allows optimizing space allocation and helps students and staff to find available rooms for a meeting or to study.

In their article, Hentschel *et al.* [117] advocate the use of supersensors (sensors with significant computing capability) with machine learning techniques to create a low cost smart campus environment. The applications include sound and motion sensors for performing room occupancy census and allowing building users to locate a meeting room currently free or a quiet study area.

In two publications, Valks *et al.* focused on the tools to measure real-time space use, whose functions aside from monitoring are to help finding study places, book meeting rooms and optimize workplace comfort. A survey at 13 Dutch universities [118] gave answers to why they use these tools, what is measured, and the employed methods. They foresee an increase in use of real-time measurements, both in smart tools for users and in monitoring the use of teaching spaces, which is currently still done manually at most universities. Covering 27 case studies in Dutch universities, international universities, and in other organizations [119], the authors evaluated smart campus tools from a functional perspective rather than a technical one to find out how they support users, save energy or help make better decisions on the future campus. The observed results suggest that smart campus tools have a high potential to further improve the use of spaces and campus management.

VII. SMART PEOPLE

Training people is the main purpose of universities and colleges. Over the last years, “smart” educational technologies, learning environments and teaching approaches have emerged. Furthermore, COVID-19 pandemics accelerated the on-going changes in the way people are trained. So-called mobile and ubiquitous learning strategies are gaining in popularity. We are witnessing a shift from the traditional learning environment (perceived as formal, passive, direct and “push”) to a modern one (perceived as informal, active, collaborative, social and “pull”) [120]. In 2016, the US National Science Foundation (NSF) elaborated a list of six “big research ideas”, one of which was shaping the human-technology frontier. The literature on smart campuses reveals many different ways in which technology and smartness can be used to improve and extend human learning and experience [121]. Authors also discuss the challenges and obstacles when moving in that direction.

Figure 14a shows the relevant recurring terms in titles and abstracts and Fig. 14b illustrates the recurring themes in the papers. Numbers in brackets in the figure point to the references reported at the end of the paper that cover a

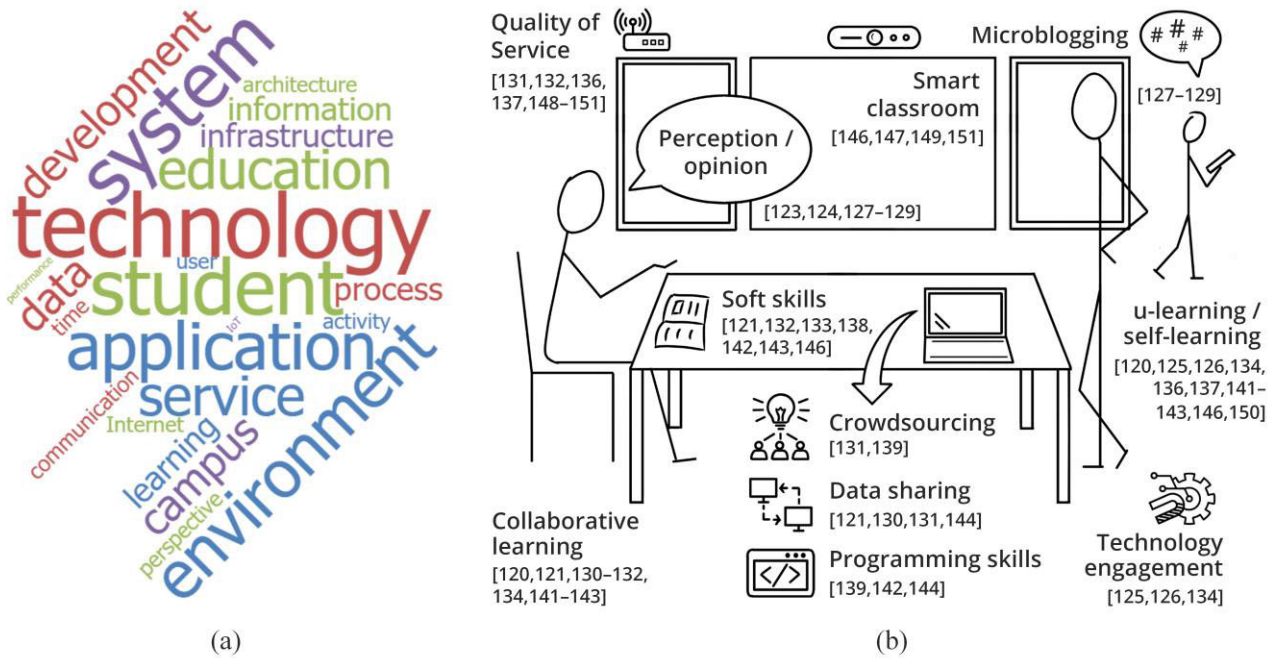


FIGURE 14. Results for the smart people category: (a) Cloud of terms in titles and abstracts (six or more occurrences); (b) Distribution of aspects covered in publications.

specific aspect. Collaboration between students for enhanced learning techniques and between the different stakeholders constitutes the heart of the sustainability aspects of this category, presented in Fig. 15. Quality of experience is delivered by proposing new learning environments and personalizing the services. Creating agents of change can be seen as forming students to be engaged citizens, ready for the “outside world” with the needed communication skills. The few actions not related to the societal sphere such as saving energy are counted in “others”.

After analysis, the publications in the smart people category were grouped into the following subsections VII-A to VII-G: (a) understanding perceptions on smartness, (b) monitoring people’s opinion, (c) knowledge transfer and collaboration, (d) ubiquitous learning, (e) gamification and virtual learning environments, (f) student innovation, and (g) smart classrooms and conference rooms.

It is important to note that in addition to the publications reported here, many others have been published on similar topics but not necessarily with a “smart campus” tag or lens. As a result, they did not make it through the methodology that we used (see Section II). For example, Mehmood *et al.* [122] developed a personalised ubiquitous framework using leading ICTs (e.g. IoT and big data) to improve smart teaching and learning, but included no mention of “smart campus”. It would be interesting in future work to continue analyzing literature with alternative keywords that could link other publications to the smart campus concept even though their authors might not have presented it that way, in particular for subsections C, D and E.

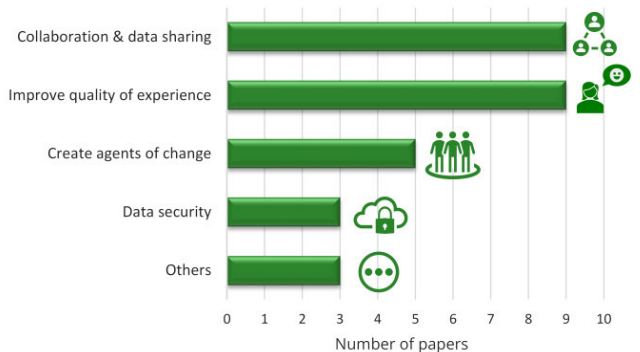


FIGURE 15. Sustainability facets related in articles of the smart people category.

A. UNDERSTANDING PERCEPTIONS ON SMARTNESS

There is a need to better understand how people (students, professors, managers, etc.) perceive the smart campus concept, how much they adhere to it, and what influences their willingness to engage in smart learning and teaching. The governing factors appear to be strongly context-related.

A survey to learn about student preferences and perception with respect to the smart concept is introduced by Příbyl *et al.* [123]. Czech Technical University in Prague (Czech Republic) and Thammasat University (Thailand) were both surveyed and differences were observed between the perception of students. CTU students did not necessarily demand more smartness on their campus, whereas TU students appeared to be eager for more. Galego *et al.* [124] used

the survey methodology developed by a European consortium to assess the smartness of the Aveiro University (Portugal). Students perceived a high degree of smartness.

Khan *et al.* [125] discussed how the adoption of mobile learning is influenced by country-specific and individual constraints. The paper aims at helping the integration of mobile devices in the education systems of the Middle East. The factors affecting adoption were (in order): national level objective, mobile learning awareness, public-private partnerships, characteristics of learners and cultural norms, and mobile learning infrastructure. The main concerns are privacy, security and obsolescence.

Factors influencing learners' technology engagement have been studied by Zhai *et al.* [126], in the context of ubiquitous game-based learning. They revealed that engagement is influenced primarily by individual expectation and social environment (e.g., peer coaching, parental support).

B. MONITORING PEOPLE'S OPINION

Social media now hold an important place in how people communicate, including on campuses. The novel capabilities to analyze in real-time the contents published on microblogs (e.g., Twitter) can be used to develop a better understanding of students' and staff's opinions, preoccupations, and perceptions, in order to provide more responsive services.

Qiu *et al.* [127] classified sentiments in Tibetan campus microblogs. They found that speech features, emoticon features and grammatical relation features reflect the microblog sentiment. Nan *et al.* [128], developed an algorithm to monitor in real-time the public opinion of students and staff from Weibo to learn the actual needs of campus users and realize personalized service. Peng *et al.* [129] proposed a model of topic detection in microblogs by mining multi-modal data (text, image, etc.) to help the smart campus enable customized education models.

C. KNOWLEDGE TRANSFER AND COLLABORATION

The dissemination of information, as well as collaboration, exchanges and sharing between students can be enhanced in a smart campus environment to improve their learning and skill development.

Zheng *et al.* [130] were interested in knowing how the social network structure influences the performance of knowledge transfer. Using a Wi-Fi hotspot-based mobile application, data on interactions between people (time, duration, etc.) were collected to construct friendship networks. They studied how knowledge spreads in different network structures and the influence of these networks on grades.

In the learning environment of a smart campus, one expects that students would be able to share information anywhere, anytime. Kadadha *et al.* [131] discussed opportunistic mobile social network (OMSN) applications in that context, i.e., a person-to-person sharing procedure allowing exchange without recourse to an Internet connection. Khamayseh *et al.* [132] introduced a framework to integrate various types of wireless networks on campuses.

Two possible applications are described: smart identification (e.g., for access to certain locations, attendance monitoring, and payment) and social collaboration (i.e., junction between social media and e-learning).

Lim and Ahn [133] designed an architecture for a campus mobile group communication system (MGCS) by using Wi-Fi. Through the system, users on campus can create community/mobile groups and maintain dynamic group membership. The concept was tested in a 1.5 km by 1.5 km district of their campus. Umam *et al.* [134] presented an ubiquitous learning model design and explained how it can improve the experience of learners using interactive internet messenger groups (IIMG) for learner-learner and learner-instructor interactions. Two lecturers of UIN Walisongo Semarang (Indonesia) and 147 learners were recruited to test IIMG, and based on a questionnaire, IIMG appeared to be effective for engaging students in the learning process and collaborating.

Griffiths *et al.* [135] described the contribution of Bluetooth beacons to a mixed pedagogy that uses digital and physical learning spaces. Based on 33 studies that the authors reviewed on this topic, the main usage of this technology was found to be on attendance monitoring, smart buildings and campuses (e.g., occupancy detector, moving on campus, etc.), and location-based dissemination of educational information (e.g., videos, guidance, etc.). The pilot deployment of Bluetooth beacons at the Hong Kong Polytechnic University is detailed in the paper.

D. UBIQUITOUS LEARNING

Ubiquitous learning (or u-learning) aims at providing learners with content, interactions, and learning opportunities anytime and anywhere. Campuses were found to be good candidates for ubiquitous learning.

Atif and Zhang [136] developed a quality of service (QoS) aware model of ubiquitous learning services based on typical learning schemes. They defined QoS indicators to regulate the load distribution and showed how resources allocation could affect the overall performance of learning schemes.

Hirsch and Ng [121] bring a new perspective in embedding mobile learning (m-learning) and cloud computing into the education sector for smart campus environment. Issues to be solved to reach cloud education include security, ownership, integration and assessment. Ng *et al.* [120] discussed context-aware social m-learning, deemed as an informal system that follows an active learning process. They argue that "pull learning" is more effective than "push learning" for modern hyper-connected digital learners. Mentioned challenges are fostering social networking in the campus, providing context-aware and personalized services, offering customized push/pull "anytime-anywhere" services, and promoting synergistic community activities.

Over the last years, there has been a sharp increase in the number of online courses offered in Chinese universities. Xu *et al.* [137] explained how 5G networks could bring new experiences to students in that context. They described an IoT

framework model and compared traditional versus two-way online class teaching models, mentioning the exponential increase of network teaching platforms used by colleges and universities. They also proposed an improved VIRE algorithm to determine the position of teachers and students in a smart campus context.

E. GAMIFICATION AND VIRTUAL LEARNING ENVIRONMENTS

Gamification and computer-generated interactive strategies as augmented reality and virtual reality are increasingly employed in learning context to enhance engagement and motivation. While it is a thriving theme in literature, apparently, it has rarely been associated with the smart campus concept in the last decade.

Chandra *et al.* [138] introduced a process and gamified interface to attract more students to participate in activities organized by faculty members, student bodies, etc., to help them develop their soft skills (e.g., teamwork, communication, entrepreneurship, planning and organization, etc.). In the proposed scheme, students can receive e-badge when they have reached a required level in a certain soft skill.

In Ref. [139], Adamkó *et al.* introduced an environment for online programming contests (also referred to as competitive programming in literature, e.g., [140]) where users (called sport programmers) can solve programming exercises and improve their skills. The environment was integrated in the smart campus platform of University of Debrecen (Hungary). It also allowed collecting data and developing value-added services by the analysis of the collected data.

Immersive learning environments to support the development of smart cities and smart campuses were studied by Soliman and Elsaadany [141]. They created links between virtual and physical environments to allow location-aware usages, including contextual navigation support, augmented attendance, locating collaborating peers, and serving learners with special needs. The authors stress the opportunity to utilize the concept of intelligent pedagogical agents (IPA) for learning services and all other types of smart city services.

F. STUDENT INNOVATION

The participation of students in the development of smart applications for their campus has been studied in a few publications.

Di Fiore *et al.* [142] tested participatory methods to design services to be added to a mobile application supporting students' activities. In the form of focus groups with students from different departments, the workshops at University of Trento (Italy) provided positive outcomes, where all groups went beyond the initial request by designing a new application in only two weeks. Coccoli *et al.* [143] described an experiment to foster collaboration skills in software engineering students with a platform-as-a-service (PaaS), in which teams of students from different Italian universities had to develop a working prototype of a web-based application. The strong relation with industry put forward in this experiment

gave outstanding results for the formation of T-shaped people. Leadership is one of the abilities that particularly stood out due to the employed student-led learning methods, where professors played a mentor role.

CampusTalk deployed at National Chiao Tung University (Taiwan) allows access to cyber and physical devices through web. Different usages are discussed by Lin *et al.* [144]. First, a total of 46 interactive physics experiments have been implemented from first-year physics textbooks. The application includes a musical glow stick application used in big events on campus (e.g., the commencement ceremony) and opportunities in terms of interactive arts. CampusTalk has also a friendly graphical user interface that allows students to create their innovations without programming.

G. SMART CLASSROOMS AND CONFERENCE ROOMS

Video recording and broadcasting are becoming mainstream in modern education.

Mazlan *et al.* [145] documented video applications within the smart campus initiative in Universiti Kebangsaan Malaysia Bangi Campus (Malaysia): video on demand (recording in each classroom), live streaming from other places than classrooms, video surveillance and real-time vehicle telemetry (parking, traffic). Li *et al.* [146] designed an intelligent video management system based on MEC and face recognition for flipped classroom (i.e. viewing lessons at home and mastering material at school). The system was thought to improve students' self-learning as well as presentation ability. It can analyze and manage video in real time and can create a video database for each student and teacher.

Shen *et al.* [147] described a smart classroom in Taiwan that automates attendance management, locates students and provides real-time student feedback. Attitudes of students towards computer science courses improved with this system. The design and implementation of a multi-source multimedia conference system assisted by cloud computing is discussed by Zhang *et al.* [148]. The authors proposed a bandwidth optimization model and introduced the concept of data forwarding priority to ensure the continuity of the data distribution. Experimental results showed that the presented system can provide a higher delivery ratio and better user experiences compared with the traditional multicasting technology.

Huang *et al.* [149] built and operated context-aware smart classrooms at Ming Chuan University (Taiwan). The classrooms include interactive boards with wireless display, RFID door access control, wall digital information board for schedules, sensors for environmental parameters, individual lighting control, etc. Several classroom modes can be triggered by voice and smart energy-saving strategies have been implemented, such as turning on-off equipment depending on what people are doing in the classroom.

Students that are not physically present on the campus can undergo long waiting time in queues for remote laboratories. To improve their experience, Huertas Celdrán *et al.* [150] developed autonomic capabilities to adapt remote laboratories

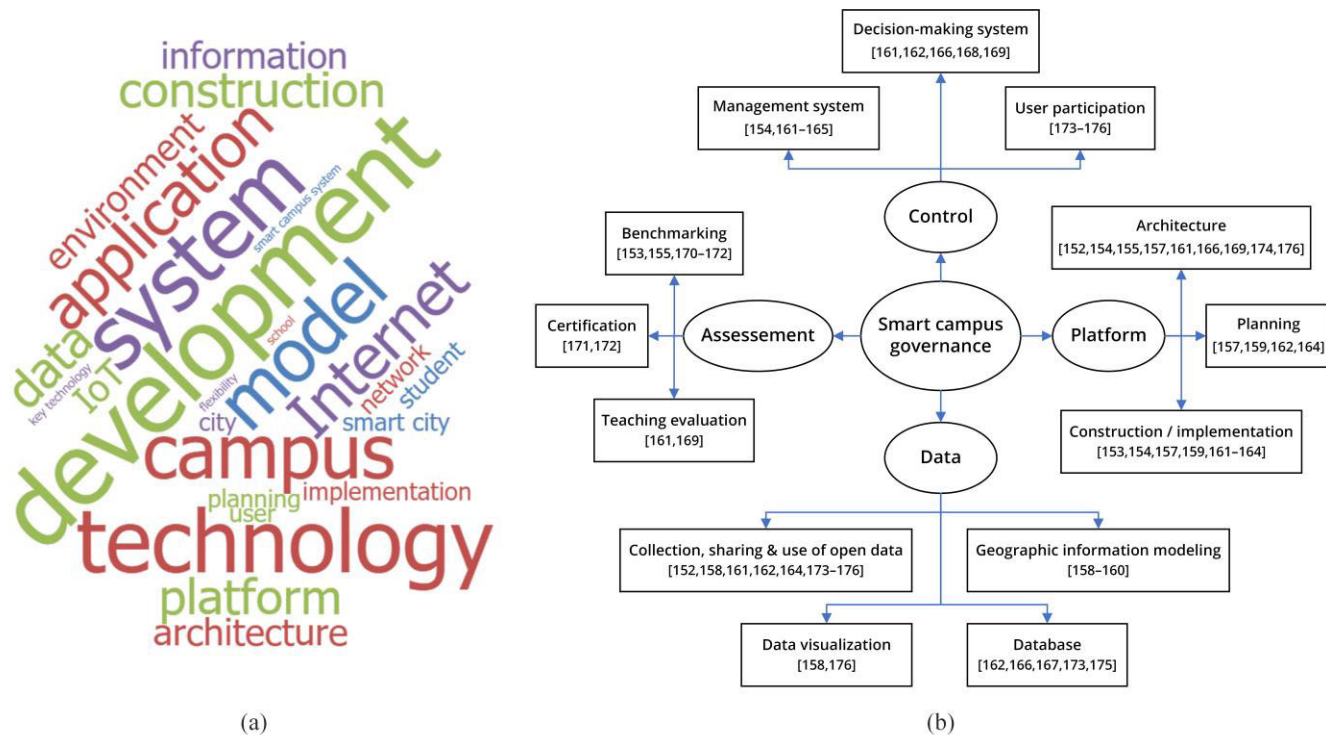


FIGURE 16. Results for the smart governance category: (a) Cloud of terms in titles and abstracts (three or more occurrences); (b) Distribution of aspects covered in publications.

configuration according to the end-user demand and dynamically change the lab service under specific circumstances. The proposed architecture is based on network function virtualization (NFV) and software-defined networking (SDN). Jianmei and Dan [151] demonstrates how the low power wireless ZigBee technology and embedded webserver GoAhead can be combined and applied for the remote control of equipment in a smart classroom. The use of a wireless sensor network (WSN) instead of the traditional wired network improves the efficiency and flexibility of the system.

VIII. SMART GOVERNANCE

This cross-disciplinary category of publications implicitly involved the other categories of this review since some sort of governance is needed in all aspects of a smart campus. In fact, the papers directly related to governance as a social science were few. This section gathers publications mostly related to the planning, deployment, management, and evaluation of smart campuses. Figure 16a shows the relevant recurring terms in titles and abstracts and Fig. 16b illustrates the recurring themes in the papers. Numbers in brackets in the figure point to the references reported at the end of the paper that covers a specific aspect.

With the arrival of a smart community the size of a campus, management of network resources (e.g., forms of data, information and hardware devices) adds another dimension to its governance system, which requires a paradigm shift and

adapted technologies. As Fortes *et al.* [152] said, “the labor of coordinating the different tasks and associated stakeholders requires a tremendous amount of effort, where dedicated and trained personnel is a must”.

Authors pointed out the need for performance indicators, benchmarks to evaluate smart campus, technological requirements and sets of standards for data format. Not many papers were found to address smart campus certifications. Gray literature, which was not included in this review, could potentially have provided more on the subject. Furthermore, and as mentioned in the previous section, the choice of keywords in the methodology of this review could have limited the number of papers found on governance, as authors might have used other keywords and prisms to present their work, even though it might potentially be linked to smart campuses.

Aspects of sustainability found in the publications are shown in Fig. 17 and they have already been discussed in the previous sections. Smartness of a campus was reported to contribute to the environment and society spheres, while the economy sphere is surprisingly not present in the literature related to governance.

Papers have been grouped into five topics, corresponding to subsections VIII-A to VIII-E: (a) multifaceted frameworks for developing smart campuses, (b) virtual campuses for planning and simulation, (c) decision-making and management systems, (d) certifications and benchmarking, and (e) open data practices.

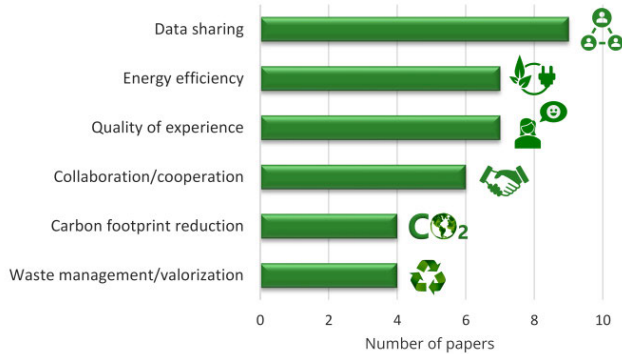


FIGURE 17. Sustainability facets related in articles of the smart governance category.

A. MULTIFACETED FRAMEWORKS FOR DEVELOPING SMART CAMPUSES

Different conceptual schematics of the smart campus concept have been developed over the years, including the one proposed here in Fig. 5. Several authors investigated frameworks and best practices for transforming a campus into a smart campus, and described examples of such initiatives in different campuses.

Pagliaro *et al.* [153] proposed an integrated framework for planning the deployment of smart campuses and applied it to La Sapienza University (Italy) campus. The method involves 5 points: planning, integration, collaboration, flexibility, scalability, and encompasses the different fields of action of the smart campus concept, which were defined as economy, environment, people, mobility and energy. As a direct follow-up work, Mattoni *et al.* [154] developed a decision-making methodology for the development of a smart campus. Two aspects are taken into account: the mutual influences among the different fields of the smart campus concept and a prioritization based on several factors.

Malatji [155] argues that the current smart campus concept does not necessarily fully suit African campuses. The framework of [153] for the development of a smart campus, which was developed for a European campus, was thus adapted to an African context. Malatji introduced key performance indicators and technological requirements, and described the efforts done at the University of Johannesburg (South Africa) in relation to the different facets of the smart campus concept.

Fortes *et al.* [152] detailed the long-term commitment of University of Málaga (Spain) to make their campus smarter and smarter. Their objective is for the campus to become a small smart city and act as an urban lab and a reference of sustainability. The approach relies on six facets: emissions, energy and water; nature and environment; health and well-being; research, teaching and innovation; mobility and ICTs. Some of their initiatives on infrastructure, management, research and learning activities are detailed in the paper, including the results of a call for proposals to foster research and innovation based on the smart campus infrastructures.

Majeed and Ali [156] proposed a model to develop a smart campus and studied the effect of IoT and cloud computing

in contemporary universities. The authors recommended creating a set of standards for data format and making the sensory data easy to manage and share. They also reported that 95% of students have agreed that the implementation of IoT infrastructure has provided a safer and more secure environment.

B. VIRTUAL CAMPUSES FOR PLANNING AND SIMULATION

In order to help the design and management of smart campus development, different types of virtual campus simulation tools have been elaborated. Many efforts have been devoted to similar topics in literature, but only publications that were tagged by their authors to the smart campus development are shown here.

Fraga-Lamas *et al.* [157] represented in detail in a radio-planning simulator the 26,000 m² campus of the University of A Coruña at (Spain) to assess the capacity and coverage of the network and the connectivity for IoT. They explained how to use the tool for planning the deployment of LoRaWAN infrastructure and showed that results agreed with empirical measurements.

Enquing *et al.* [158] introduced a smart campus platform framework with different layers: application, platform function, data service and infrastructure. They focused on the 3D geographic information modeling, including low-altitude photographic measurement for three campuses and geospatial information modeling. The 3D virtual campus can be used for spatial analysis, positioning, data loading and display, etc.

Bi *et al.* [159] developed a virtual campus through BIM and 3D GIS (geographic information system). The resulting 3D smart campus platform can be used, among other things, for construction analysis, urban planning and rail transit construction. Zhang *et al.* [160] established the digital system for the survey control system in the old campus of Wenshan University (China). Considered the basic precondition for school infrastructure construction and instruction about surveying and mapping, the authors used modern technologies (RTK, DS1) for developing the system.

C. DECISION-MAKING AND MANAGEMENT SYSTEMS

Enhancing technology capabilities and connecting devices together in campuses requires the development of adapted decision-making and management systems on which several authors have focused.

Guo [161] described the design of an automatic settlement platform (smart teaching system, unified management and data security) in the context of smart campus construction. Such platform relies on IoT and was found to enhance the management level of the institution. Different applications and results are reported, including good consumption and billing, library management, etc. Guo and Zhang [162] also presented the planning and design of a smart campus, including the deployment of IoT systems and cloud data center. The authors argued that the traditional way of construction cannot meet the development of campus scientific decisions;

therefore it is necessary to introduce the IoT on the basis of existing facilities to achieve the dynamic expansion, resource adaptation, sizing deployment and united management of the virtual data-center.

Du *et al.* [163] used the case of Shandong Normal University as an example of how to design and deploy a smart campus and how it could improve management and service capabilities. Campus mobile phone card system, campus geographic information system, library management system, room management, shuttle bus management system, news, among others, are part of the concept. The four-layer smart campus architecture, as well as the authentication and data analysis platform are introduced.

Hipwell [164] summarized how two new campuses of Birmingham City University (UK) were developed with the intention of being “intelligent” to improve business-processes, reduce energy use and carbon emissions and enhance the occupant experience. No out-of-the-box product was found to meet the requirements needed in terms of intelligence, and it was decided to include integrated building management, environmental and security systems into the existing service oriented architecture (SOA).

Guo *et al.* [165] proposed a service-oriented network architecture for IoT called Smart Service System (3S), aiming to achieve the flexible allocation and dynamic management of network resources. Focusing on the network resources optimization design algorithm, the authors also provided a semantic description method for IoT services, a resource representation model and a resource management model. Zhan *et al.* [166] analyzed the characteristics of smart campuses and the overall framework of the decision support system. They stressed the necessity of implementing a complete smart campus decision-support system based on the actual situation of each department of the university to ensure a more convenient learning and working environment for teachers and students. Oliveira *et al.* [167] reported the result of a living campus experiment at the University of Melbourne (Australia), in which an intelligent middleware platform supports capture of distributed and heterogeneous environmental sensor data in outdoor public learning spaces. The up-to-date information reporting the use of those spaces and users’ routine combined with local perspectives offers new opportunities for better management and improved tools for planning and policymaking.

In [168], Wu *et al.* mentioned the difficulties for universities to identify students in a difficult financial situation. A smart campus system is proposed to detect these students, support the decision-making on the subsidy offered to them and alert counselors and psychological support, based on information such as the amount and diversity of goods consumed on the campus, characteristics of students’ campus activities, etc. Resampling was successfully used as an imbalanced data processing method, along with the random forest for classification. The system has been put in practice at Xi’an Jiaotong University and was found to improve the efficiency and quality of student management.

Xu *et al.* [169] proposed a smart campus architecture model, with a focus on teaching performance evaluation. The model has different layers: intelligent sensing, data communication, intelligent processing, and intelligent recommendation. An evaluation index was constructed and tested, based on AHP (analytic hierarchy process), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), and PCA (principal component analysis). Big data generated by online courses (e.g., number of logins, etc.) can be exploited for that purpose.

D. CERTIFICATIONS AND BENCHMARKING

As part of a smart campus initiative, it could be useful to evaluate the advances of a campus in terms of smartness and sustainability, and to compare its realizations with those of others. This benchmarking can be achieved with different types of certification. The certification exercise can also serve for the mobilization of a campus community, and can help develop a branding for the university.

Pompei *et al.* [170] indicated that the development of a campus into a smart campus requires an evaluation framework with composite indicators. They defined such indicators for different facets of the smart campus concept. The approach includes standardization of variables and data, and then aggregation and weighting. It was also applied to the engineering department of La Sapienza University as a case study.

Data in Ukraine showed values of total energy intensity ranging from 31.6 to 608 kWh/m²y, with an average of 174 kWh/m²y. This large variability is explained, among other things, by differences in climatic conditions and activities on campuses. Deshko and Shevchenko [171] developed a methodology for energy certification of university campuses in that country to better assess whether a campus is energy-efficient given its context and compared to others with which it shares similarities.

In 2007, a group of college and university presidents signed the American College and University Presidents’ Climate Commitment (ACUPCC), a commitment to pursue the goal of carbon neutrality on their campuses. Sirianni and O’Hara [172] looked at the actions chosen to achieve this objective and the results two years after taking the commitment. They found that schools focusing on improving energy efficiency have achieved swift reductions of emissions, whereas those pledging to use green power were generally already utilizing it and did not improve their systems to achieve additional reduction. The results also suggest that schools choose to make reductions where they are the least costly instead of attempting to reduce in areas where emissions are highest.

E. OPEN DATA PRACTICES

Vasileva *et al.* [173] argue that making data publicly available could bring many benefits to different stakeholders and users for deploying a smart campus. Through stakeholder interviews and user surveys on a UK university campus, a list of aspects affecting positively or negatively the participants was

established. It was found that the main perceived issues were data privacy issues, data security and misuse, cyber security, poor and inconsistent delivery, costs, failure of technology and less human interaction. The authors also verified which campus-related data (e.g., energy use in buildings, use of hoppers buses, etc.) the participants thought should be shared and which ones they would personally be interested in gaining access to.

At University of Nice-Sophia Antipolis, a project aim to equip a new campus named SophiaTech with sensors collecting data about campus' usage. Cecchinel *et al.* [174] described this prototypical example of Big Data application as an open platform letting final users build their own innovative services on top of the collected (open) data. The architecture goes from sensors to data management and would support users who want to set up a research or production infrastructure to collect very large datasets. Similarly, Monti *et al.* [175] designed and developed an infrastructure made of sensors to collect real-time data in a university campus and a web-based application for people to interact with data. These datasets can be investigated by students and include information from outdoor environmental sensors (IAQ, T, humidity, pressure), indoor occupancy based on CO₂ and infrared cam, noise level.

Haghi *et al.* [176] described their fast-paced development experience of a generic smart campus IoT platform by only four junior undergraduate students who had no prior knowledge about IoT, where the design, implementation, and deployment was completed in three months. The platform enables the aggregation and open distribution of campus IoT data related to student life and academic activities. Contributors would use the platform to collect and generate data, and users looking to utilize data, e.g., for application development, would have access to both real-time streams and historical datasets.

IX. SMART DATA

Backbone to the smart campus paradigm, the acquisition, analysis, exchange, and protection of data is at the heart of this section. Without referring to a specific application, the papers of this category discuss the latest systems, technologies, and procedures that are indispensable to build and operate an efficient and secure smart campus. Following the review of the publications, "smart data" are organized data, protected from malicious intent, and especially, accessible by the authorized persons or devices. Figure 18a shows the relevant recurring terms in title and abstract and Fig. 18b illustrates the recurring themes in the papers, organized by layers of a typical IoT architecture. Numbers in brackets in the figure point to the references reported at the end of the paper that cover a specific aspect. Note that we haven't provided a summary of sustainability facets within the smart data category since it was not addressed in the publications.

After analysis, the publications in the smart data category were grouped in the following subsections IX-A to IX-E: (a) wireless sensor networks and wireless infrastructures,

(b) middleware and IoT naming scheme, (c) context-awareness, (d) data storage security and attack simulation, and (e) authentication.

A. WIRELESS SENSOR NETWORKS AND WIRELESS INFRASTRUCTURES

A wireless sensor network (WSN) is a group of dedicated (ad hoc) and autonomous sensors called "nodes" relying on wireless connectivity to monitor and transmit data to a "sink", habitually a central location like a server. Thus, it requires a certain wireless infrastructure, which can be based on different kinds of communication technologies depending on the system's nature and the distance to travel. WSNs and wireless infrastructures are the subject of growing interest in all spheres of society.

According to Del-Valle-Soto *et al.* [177], WSN is considered the most critical element of the IoT model, allowing scalability and supporting its integration with the current Internet architecture. The authors compared four IoT protocols (BLE, LoRaWAN, Wi-Fi and ZigBee), each with two energy optimization schemes. Energy consumption is a key aspect since WSNs are usually battery powered. ZigBee turned out to be the protocol with the lowest consumption, both with the collaborative and cooperative schemes. In another paper [178], the authors compare three routing protocols of different nature (proactive, hybrid and reactive nature) in order to analyze the information delivery and measure the performance of a network. The simulation and experimentation in a real campus showed that the hybrid protocol has 10% better performance than the others, based on parameters such as route validity, response time, delay, resilience and energy.

Loriot *et al.* [179] studied the use of LoRaWAN in a large-scale demonstrator of the Smart City conducted at the Scientific Campus of the University of Lille (France). Developed by LoRa Alliance, the open protocol LoRaWAN is deemed well adapted to smart campus projects since it allows interoperability of many devices. Its employment of spectrum spreading modulation enables low energy consumption and end-to-end secure communication with low data rates. Wang *et al.* [180] evaluated the performance of LoRa-based IoT applications deployed in the National Chiao Tung University campus (Taiwan). The LoRaWAN transmission performance was measured under different contexts by using an air quality monitoring system. The authors showed how packet losses were affected by the distance between the end-device and the gateway, the transmit power, the payload length, the antenna angle, the time of day, and the weather conditions. They observed as well that the transmission may be severely interfered with by the nearby 4G base.

Trilles *et al.* [181] deployed an IoT "sensorized" platform called Senviro at Universitat Jaume I (Spain), a horizontal/transversal platform with interoperable data and services to offer open access and facilitate the creation of applications. To enhance interoperability between IoT and smart city solutions, GIScience standards and solutions have been applied.

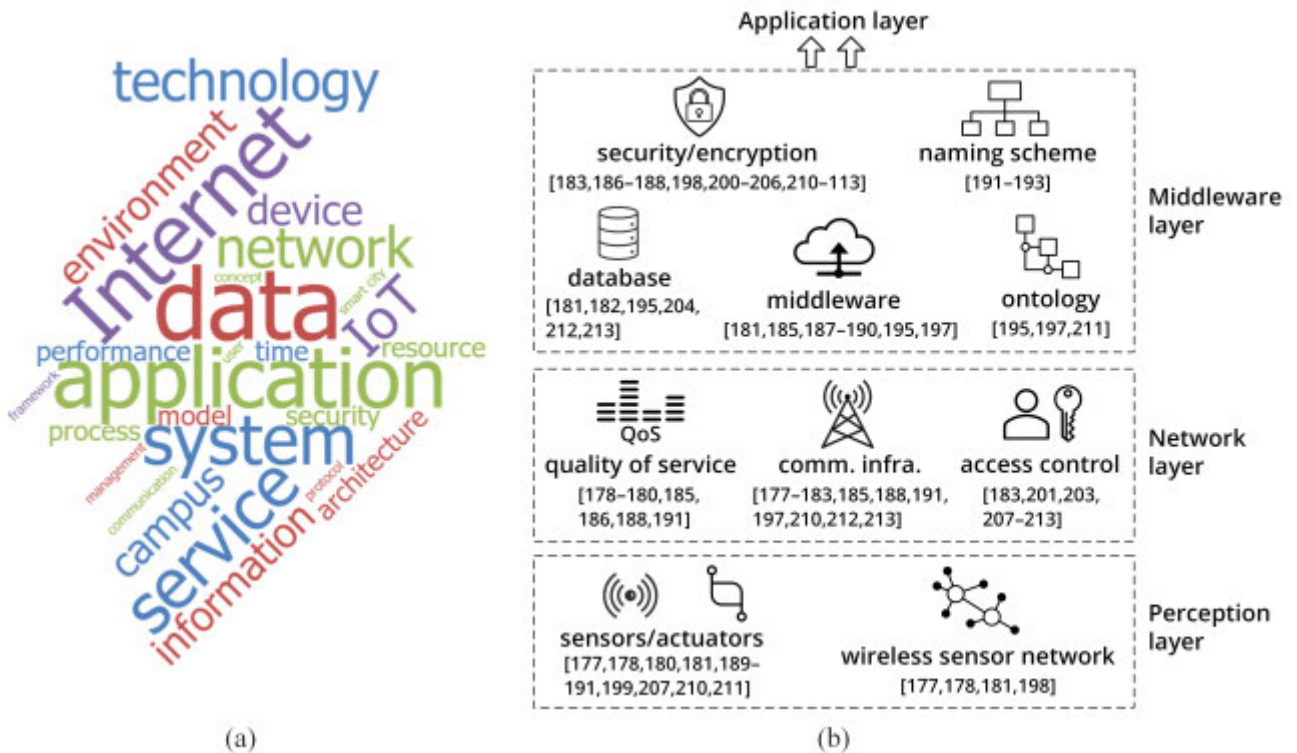


FIGURE 18. Results for the smart data category: (a) Cloud of terms in titles and abstracts (ten or more occurrences); (b) Distribution of aspects covered in publications.

Van Merode *et al.* [182] developed a hardware and software smart campus solution to deliver individual information for students, teachers and visitors depending on their profile and time of day. For the choice of protocol, the authors state that the best compromise in price, distance and speed is provided by BLE, the low-cost and low-power PAN of Bluetooth. Issues still to be solved by the scientific community include triangulation for an exact position determination, static interference with indoor-usage due to walls, dynamic interference due to people, and interference due to multiple beacons in one location.

The RFID technology has many advantages like rapid moving object identification that make it appropriate for smart campus applications. Xiao *et al.* [183] mentioned many functions, such as identity recognition, payment, access control, attendance, library, dormitory and vehicle management. The issue of weak data security during transmission process requires the legitimacy authentication of electronic tag and reader to be completed in the background through an encrypted handshake.

Edge computing, a key enabler for many recent technologies like 5G and IoT, brings the service and utilities of cloud computing closer to the end user and is characterized by fast processing and quick application response time [184]. Li *et al.* [185] proposed an integrated utility-based cache placement strategy in edge computing system. Executing a portion of applications on the edge servers can reduce the

amount of data transmitted in the network, reducing latency and energy consumption. Similarly, Xu *et al.* [186] presented a trustworthy edge caching and bandwidth allocation scheme for mobile users, motivated by the limited caching and bandwidth capacities of edge nodes. The simulation results show that the proposed scheme can improve the QoE (quality of experience) of mobile users and prevent the attacks of malicious edge nodes.

B. MIDDLEWARE AND IoT NAMING SCHEME

In an IoT architecture, the middleware layer is between the hardware layer (comprising computational devices and sensors), and the application layer. It is a software platform that enables communication between different systems that are otherwise incompatible. In literature, IoT middleware platforms are also called IoT middleware solutions or simply IoT platforms [187]. Naming IoT devices is also crucial to ensure efficient and secure communication, thus research efforts have been made on improved naming schemes and on autoconfiguration.

Da Cruz *et al.* [187] presented a performance comparison of 11 open-source IoT middleware solutions with quantitative and qualitative metrics, including a proprietary solution developed at the National Institute of Telecommunications (Brazil), also called Inatel. Since 70% of IoT devices in smart cities are at risk of being attacked, data security is an aspect to which the authors gave particular attention.

The Sitewhere middleware platform presented the best performance for the considered scenario and the parameters under study. Tan and Wang [188] discussed the technical issues that need to be addressed to obtain the “real” IoT, such as the interoperability problem and the lack of global open standard. In their 2010 paper, the authors shared their concern about the exponential increase of traffic and storage due to exchanged information between connected objects. They proposed to add a “coordination” layer into the IoT architecture design, since “a toothbrush [does not] need to “talk” to a fridge”. Ten years later, the coordination function is now taken care of by the middleware platform.

Villegas-Ch *et al.* [189] proposed a guide to move from a traditional campus to a smart campus with a Hadoop middleware platform following three main axes. The IoT obtains environmental data, cloud computing centralizes the data in internal or external infrastructure, and big data analyses and manages the data. In Ref. [190], the entire distribution of this framework is tested and refined by treating and monitoring the voltage variation data of the smart campus data center. The authors pointed out that the comfort and benefits of technology must be developed in a sustainable environment, and that the use of open-source tools makes the method generic, enabling its implementation on any type of campus.

Arshad *et al.* [191] proposed a hybrid naming scheme that names contents using hierarchical and flat components to support scalable and secure push and pull communication. Simulation with an IoT-based smart campus scenario demonstrated that the proposed scheme is a significant improvement and eliminates the loop problem associated with CCN (Content Centric Networking) protocol by implementing “unicast” protocol on the source nodes. Similarly, Nour *et al.* [192] designed a hybrid multilayer naming scheme to help identify services and devices in an IoT network. The authors demonstrated that it drastically reduces memory consumption, lookup time, routing and forwarding overhead, and enhances the overall IoT communication.

Lee *et al.* [193] proposed a new naming framework for Domain Name System (DNS) called DNSNA (DSN Name Autoconfiguration) for IoT devices in Internet Protocol (IP) version 6 (IPv6) and IP version 4 (IPv4) networks. Using a unicast protocol, DNSNA removes the burden of manually configuring the DNS names of large-scale IoT network devices. In an IPv6 network, it can reduce the average number of packets by 60.8% and the accumulated packet volume by 97% in comparison with multicast DNS naming service.

C. CONTEXT-AWARENESS

Context-awareness is a feature of smart mobile devices that is essential in ubiquitous computing. In the context-aware software development process, it plays an important role in defining the core data that could be processed in certain applications, such as data for deducing the location of a user [194].

Pointing out the mismatch between context-awareness and traditional information systems with relational databases,

Maran *et al.* [195] presented an integration model that allows retrieving relational data in context without the necessity to change the originally-used relational queries. The implementation of the model in a case study revealed the possibility of employing an ontology frequently used in ubiquitous middleware as an extra filtering layer for information systems instead of recreating queries. Mok and Min [196] developed an ontology-based context-aware model using a Bayesian network method to lower the relation complexity between objects. Its evaluation in a smart campus environment for various scenarios showed its flexibility and capacity for reasoning uncertain situations. Verstaavel *et al.* [197] deployed two different smart campus platforms at the University of Wollongong (Australia) and the University of Toulouse (France) that can cooperate and exchange information based on the same use of a standardized service layer (oneM2M standard). The authors proposed an innovative framework that relies on an ontology-based model and context-awareness for composing new services on-the-fly.

Yang *et al.* [198] discussed the challenges in integrating service data on smart campuses and the advantages of a smart campus over a traditional campus. The paper also relates the design of a context-aware service discovery model and provides an application example, the collection of payment data done by the intelligent payment platform, where only a mobile phone is needed. Khabou *et al.* [199] discussed the development of context-aware applications, specifically the analysis phase. The authors defined the context classification step that attributes context categories for each context parameter and proposed the context change detection step that targets detecting context changes with a threshold comparison technique.

D. DATA STORAGE SECURITY AND ATTACK SIMULATION

Whether it is for securing private data or preventing virus spread, digital networks must always remain up-to-date against the ever-evolving cyber threats. The safety of information is crucial in university campuses (identity, scientific research and management information, etc.) so that a constant research effort is needed on that topic.

Popescu *et al.* [200] presented a prototype solution to provide a high level of security and high data confidentiality in a smart campus, intended to be applied at University of Oradea (Romania). To protect data-at-rest against unauthorized users in cloud computing, the authors proposed a fifth layer to the existing four-layer cloud security architecture, using steganography to hide the information in images. Shen *et al.* [201] developed and tested a cloud-assisted two-factor protection mechanism for public data in smart campus. To decrypt the ciphertext stored in the cloud computing storage, the user needs to gather their secret key and security equipment at the same time. This mechanism proved to be secure, efficient and practical.

Smart campus system may be threatened by different attacks from viruses, trojan horses or steganography. To prevent privacy disclosure, Xiang *et al.* [202] developed

a linguistic steganalysis method based on word embedding for detecting the stego texts generated by synonym substitutions. The experimental results showed that it can effectively detect the synonym substitution-based steganography and improvement could be made using particular corpus or good language model. Xia *et al.* [203] introduced a privacy-preserving computation outsourcing protocol for the LBP (local binary patterns) feature over huge encrypted images. The extracted features can be applied to many applications, such as texture classification, image retrieval and face recognition.

Using a smart campus prototype, Zhang *et al.* [204] presented a new direction that uses encryption instead of anonymization for preserving user privacy in wireless network traces. Two practical encryption techniques were presented to encrypt time ranges. They provide much stronger security guarantee than existing order-preserving encryption schemes, and their evaluation showed they only lead to moderate increase in storage, network bandwidth and computation overhead.

Tian *et al.* [205] proposed an object-dependent method named C2RS to analyze the evidence of illegal activity. Based on a cyber-range, a virtual environment that can be used for cyber warfare training and to evaluate security systems in various cyber threat scenarios, the method provides tools to strengthen the stability, security and performance of smart campus cyberinfrastructures. Wang *et al.* [206] developed a model that can simulate the spread of a virus in smart campus networks to improve their security and robustness. Applying a differential power system to describe a single network node, it then uses graph theory and linear equations to link the evolution of each node with changes throughout the entire network.

E. AUTHENTICATION

Authentication and identification of devices connected to a smart campus network is a key part of the security system. Special attention is accorded to IoT devices, since their ubiquitous nature makes them easier to infiltrate. Being mindful of anomalous behavior is also essential for detecting malicious nodes that are already in the monitoring system, where intrusion or prevention systems are powerless [207].

A hybrid access control system of user authentication, inter- and intra-system authorization is constructed by Liu *et al.* [208] in a smart campus. Two caching mechanisms based on group and role were designed to optimize the authorization decision. The model was deemed flexible, reliable, and could meet the needs of large-scale distributed access control in smart campus.

Rehman *et al.* [209] modeled the registration system of a smart campus using Unified Modeling Language (UML) sequence diagram, Non-Deterministic Finite Automata (NFA) and Vienna Development Method Specification Language (VDM-SL). The model is efficient and automated and has many components and operations for managing students' records.

Ye *et al.* [207] proposed an IoT system level authentication protocol independent of university IT department to achieve mutual authentication for both IoT devices and users. Also integrating credential auto update and distribution schemes for different groups of users, the authors demonstrated their approach with the IoT green roof monitoring system for environmental surveillance on a campus of University of Dayton (USA). To help operators of smart campuses identify and classify their IoT devices and detect anomalous behavior, Sivanathan *et al.* [210] characterized IoT traffic at the network-level. By collecting traffic traces over 3 weeks, the authors indicated that their classification method can not only distinguish IoT from non-IoT traffic, but also identify specific IoT devices with over 95% accuracy. Yousefnezhad *et al.* [211] developed Measurement-based Device Identification (MeDI), a framework based on device behavior or device profile. It monitors the data packets coming from smart devices to protect the server from receiving and spreading false data. Three identification methods were tested with a lab dataset of the smart campus Otaniemi3D (Finland) IoT environment.

Zhang [212] presented an enhanced lightweight authentication protocol to meet the security requirements of RFID systems. It reduces computational complexity of backend database, can resist many common attacks, and greatly increases the availability, scalability and compatibility of large-scale RFID systems. Zheng *et al.* [213] introduced a mutual authentication protocol applicable for the widely used RFID systems in smart campus, aiming to enhance system safety and privacy while reducing label cost. It effectively resists tracking, forgery, and many other attacks.

X. CHALLENGES, OPEN QUESTIONS FOR RESEARCH AND CONCLUSION

In order to conclude the present review, we formulated seven of the greatest open questions and challenges related to smart campuses that stood out while reviewing the scientific literature. During the first steps of elaborating this review, presenting these challenges and open questions at the end of each category section was considered. However, it quickly appeared that most questions were overlapping over more than one category. Therefore, it was decided to present them at the end of the paper. Note that they are not listed in order of importance.

(i) **How can smart campuses go hand in hand with sustainable development?** In the previous sections, we underlined the sustainability facets covered in the different papers that were analyzed (see Figs. 7, 9, 11, 13, 15 and 17). Behind this exercise was the premise that in order to achieve a truly smart campus, sustainability, broadly defined, is required. Even though sustainable development was present in the background of many papers, we found no clear and encompassing attempts to link explicitly sustainable development principles to the smart campus concept. In promoting smart campuses, we should ensure that there is no real or perceived clash between high-tech, sophisticated, automated strategies

and biophilic, green, environmentally engaged approaches. Based on the literature review, it appears that there is a need to clarify the relations between smartness and sustainability of campuses.

(ii) How can smart campuses contribute to the ongoing energy transition? The enormous impact of energy on all spheres of sustainability is unmistakable, and evidence that the world has engaged in a so-called energy transition abounds [214]. Major aspects of the ongoing energy transition should ideally be more strongly integrated: operational energy decision-making/consumption, research and education. Because each of these characteristics is prevalent on university and college campuses, such organizations are uniquely positioned to leverage their scope and scale. Scope, because universities represent important energy consumers and can decide to a great extent how they procure and generate power and heat, and how they use them. Furthermore, universities and campuses represent a microcosm of larger entities, given their purview over a number of technical opportunities and challenges, while also taking into consideration legal, political and economic levels. Universities and campuses also represent a kind of “sweet-spot” in terms of scale: big enough to matter, but small enough to be tractable. Figure 1 illustrates that the energy transition can be realized at different scales, including on a smart campus. Optimization of myriad energy systems (e.g., heating, chilling, power production, etc.) is a complex task that relies on the integration of physical and cyber systems, robust data acquisition and processing, and increasingly, artificial intelligence and advanced computing techniques. Clearly, locality, geography, and other contextual factors can heavily influence outcomes and replicability of solutions. As such, there is an essential need to advance comparable energy transition frameworks at the campus scale, and disseminate results and best practices. Given that the energy impact of people (i.e., occupants of buildings, cars, etc.), as compared to systems, is critically important, the educational and training missions of universities can serve to further advance knowledge on multiple dimensions.

(iii) How can privacy, consent and ethics be enforced in a smart campus? Sections V to VIII describe reported applications that are seen as invasive by many people. For example, depending on individuals, their own context and their culture, face-recognition and profiling of students can be considered as an invasion of privacy. The question of where to draw the line between data collection and privacy is extremely important on a smart campus. In our opinion, consent and transparency are required when designing a smart campus platform from an ethical perspective and to ensure people’s acceptance. In fact, these concerns are recurrent in ICTs in general, and in particular in the literature on the different smartness scales highlighted in Fig. 1 (e.g., [215]). However, the body of literature analyzed here (i.e., publications identified with smart campuses) often fails to address the topic in the description of applications that are reported. Furthermore, no publication on smart campuses within the

scholarship of ethics and privacy came out from the queries in the databases. This might indicate that more collaboration and sharing between specialists in these topics and researchers associated to smart campuses could be useful. More reflections on the ethical and privacy issues specifically related to smart campuses are needed.

(iv) What makes a smart campus acceptable and well perceived by people? It is impossible to imagine a successful smart campus without the commitment and support of its people. As in any transformational project, the development of smart campuses is likely to require excellent change management practices allowing open communication between stakeholders, goal monitoring and training. It is important to recognize that not everyone might see an interest or an added value in investing resources and time into smart campus projects, which might translate into opposition or simply indifference. We discussed earlier about a few studies on people’s perception of smart campuses and their wish to develop (or not) a campus with a higher level of smartness. However, little information was found in the publications that were analyzed here on the features that make a smart campus project accepted, adapted and successful within their university communities. In fact, the expertise and work on social acceptance, change management and communication did not seem to have percolated into the smart campus publications that were surveyed, either due to the literature review methodology that we employed or to the lack of connections between these disciplines and smart campus technology research. More knowledge on this topic could certainly guide current and future research efforts towards technologies and approaches that are better suited to their context. It would also benefit the development of smart campus governance and decision-making frameworks.

(v) How to find the proper smartness balance in learning & teaching in smart campuses? The development of new learning & teaching practices (and the associated infrastructures) that would bring out advantages compared to more “traditional” methods is a vast field of research in itself. However, only a small sample of these studies actually appeared in the set of papers analyzed here, pointing to a potential lack of overlap between the smart campus and learning & teaching literatures. There is a clear enthusiasm in the surveyed literature for online, ubiquitous or mobile learning, where students can learn outside the traditional classroom model, even though negative outcomes such as higher drop-out were also reported [135]. However, this body of work provides little insight on the “ideal” equilibrium between the various ways of learning & teaching in different smart campus contexts, and the focus is often put on technologies and infrastructures. A better integration between the recent advances in pedagogy and smart campus research would help in that respect. In fact, when developing “smart learning” technologies, one can recall the words of computer scientist Weizenbaum [216] who suggested back in 1976 a ban on “all projects that substitute a computer system for a human function that involves interpersonal respect, understanding, and

love”. At the time of writing this paper, many are experiencing remote education imposed by the COVID-19 pandemics, and realize the usefulness and potential of learning and teaching technologies. At the same time, the lockdown exposed the value of human relationships and campus experience, which have been lacking for many recently. The situation illustrates well the benefits and limits of many technologies and infrastructures that are developed within the smart campus concept.

(vi) How can universities implement open data policies and rely on participative strategies and crowdsourcing?

Smart governance provides users with mechanisms to participate in decision-making and in public services [157]. Many professors and students could be interested to use data from smart campuses for educational and research purposes, “which is felt to be difficult to acquire through the university for their studies” [173]. Uncooperative governing bodies can see such initiatives as a waste of time or fear potential problems regarding privacy or competitiveness. The concept of open data may be perceived as the opposite of data privacy. Balancing utility and privacy in open data is one of the functions that need to be integrated to smart decision-making systems. Additionally, how to filter, organize in a suitable way and make available a huge amount of data is not trivial. Several authors think that making a user interface more accessible is a promising avenue, where the open data can be used to create new content and applications benefiting the whole campus community. It cultivates not only the collaborative spirit between campus members and with other institutes, but also the talents of students and staff. More examples and case studies are needed to demonstrate the feasibility and benefits of this approach.

(vii) How to enhance interoperability and promote open standards?

Within the smart campus paradigm, achieving a functional coexistence of very heterogeneous elements (in other words, interoperability) presents a real challenge to developers. It requires “the mastery of protocols and standards to leverage system interoperability due to the large number of products, platforms, and competing applications that coexist in the IoT” [36]. Many authors complain about the lack of open standards. The subject of interoperability is often mentioned in the publications of all the categories and sometimes even generates cynicism in literature. For instance, Kumar et al. [217] think that “expecting to reach interoperability among devices by enforcing a universal standard is somewhat innocent”. However, a lot of effort is currently directed to creating standardized IoT architectures to address the interoperability problem [197]. Middleware development and the quest for open standards are research subjects that are essential to the success of the smart campus model.

In order to conclude this review, it can be said that a smart campus can improve the sustainability performance of a university/college and have the potential to enhance research experience by making it easier to access data, facilities, planning, etc. The literature which this review studied does not cover the entire research activities on smart campuses: the reality may be ahead of the published papers. For example,

each RLS region hosts ongoing projects that have not yet been described in publications. According to the authors, a city or a region cannot claim to be “smart” if it does not have a university campus which is a model for sustainable development. Putting science at the heart of “smartness” is a way to bring science closer to citizens, and a smart campus needs to be close to municipal decision-makers and policymakers to influence its city and region, and vice versa.

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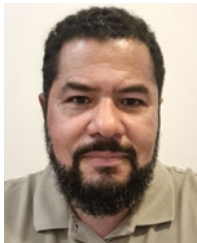


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