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Campus City Project: Challenge Living Lab for Smart Cities

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Abstract: This work presents the Campus City initiative followed by the Challenge Living Lab platform to promote research, innovation, and entrepreneurship with the intention to create urban infrastructure and creative talent (human resources) that solves different community, industrial and government Pain Points within a Smart City ecosystem. The main contribution of this work is to present a working model and the open innovation ecosystem used in Tecnologico de Monterrey that could be used as both, a learning mechanism as well as a base model for scaling it up into a Smart Campus and Smart City. Moreover, this work presents the Smart Energy challenge as an example of a pedagogic opportunity for the development of competencies. This included the pedagogic design of the challenge, the methodology followed by the students and the results. Finally, a discussion on the findings and learnings of the model and challenge implementation. Results showed that Campus City initiative and the Challenge Living Lab allows the identification of highly relevant and meaningful challenges while providing a pedagogic framework in which students are highly motivated, engaged, and prepared to tackle different problems that involve government, community, industry, and academia.

Keywords: smart water/energy/mobility; open innovation; challenge living lab; smart city; challenge-based learning

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1. Introduction

Uncontrolled and rapid urban growth has given rise to different issues affecting Quality of Life (QoL) [1–5]. QoL is defined by the World Health Organization as "individuals' perception of their position in life in the context of the culture and value systems in which they live, and in relation to their goals, expectations, standards and concerns" [6] and relates to their happiness, security, well-being, ecology, resilience, and global awareness. Some of these problems affecting QoL include energy generation and distribution, traffic (mobility), unequal housing, health, education, environment (air, water, soil), etc. [1,7,8]. A collaborative framework involving the citizens, government, academia, and private sector is crucial to minimize the impact of these problems. The use of integrated and interconnected technological developments, supported by information and data, enables this framework to propose different solutions to improve the overall QoL of the citizens [2,9–11]. This concept is referred to as a Smart City and could be described as a living laboratory or hubs driven by innovation to meet global standards [12,13], in which political, social and environmental decisions are made based on data [14].

Figure 1 depicts the Smart City logical framework, including its various components and stakeholders or key actors. This framework begins with the needs and challenges the city is facing, called Pain Points [15]. A crucial step is an initial selective process or screening, during which the technical, economical, and social feasibility is considered by all stakeholders participating in the decision making process: citizens, government, academia, private sector, investors, and entrepreneurs (upper right part of Figure 1) [1,16]. The creation or modernization of public policies is a crucial step within this framework, especially in regards to the material, economic and human resources available to contribute to these projects and reach the goal of transforming a community or a city into a smart environment [16]. Moreover, feedback cycles are important to ensure an effective and efficient implementation of the project solutions. Feedback is based on data, digital technologies and interconnected visualization dashboards (Internet of Things, Information Systems, Artificial Intelligence etc. [2,11]) that allow the dissemination and socialization of the finished and ongoing projects. Finally, the framework's main goal is to affect the different dimensions related to the Smart City's habitability and QoL.

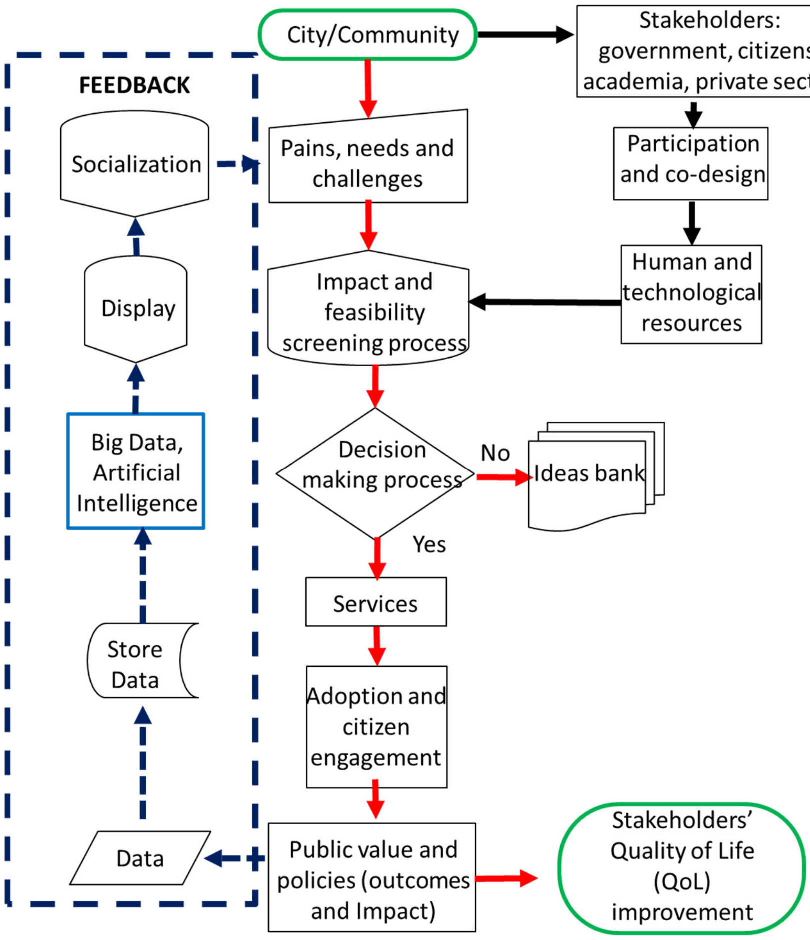

Figure 1. Logical framework of a Smart City.

At this point, it is important to highlight the role of the academic institution. The university becomes a key stakeholder for: (1) the identification of solutions for the Pain Points based on innovation, interconnectivity, and research and, (2) the development of human resources with the necessary skills to provide solutions, management, and technology at different levels in a Smart City. Additionally, the active involvement of research institutes and universities is required to sustain an open innovation ecosystem that could drive technological development [17,18].

In 2015, the United States launched an initiative to promote research, innovation, and entrepreneurship (RIE) in university campuses called the "Smart City Challenge" project [19]. With the participation of 78 cities, the project concluded that citizen wellbeing is highly influenced by connectivity, information about the city's resources and the need for better mobility. Moreover, various initiatives have studied and developed the transformation of university campuses into smart living laboratories, through which different projects could potentially be scaled up to solve the Pain Points of a city [20–23]. Even though these works provide insight into the operation, organization, technological infrastructure, and methods used, only few studies provide some information on how they could use the Smart Campus concept as a learning mechanism for students [22,24,25]. Further work is required to develop Smart Campuses with educational models that can meet the needs of a Smart City while enhancing the learning experience of the students and providing them with the knowledge and skills required to solve different real-life challenges or Pain Points.

Inspired by the RIE results and the above-mentioned needs, the transformation of the Tecnologico de Monterrey university's main campus in the city of Monterrey, Mexico, and of its neighboring communities was established as a key part of its strategic plan for 2020: to generate sustainable spaces and sustainable conditions for RIE. This project, called Distrito Tec, focuses on enabling the creation of a dynamic, safe and inspiring community, one that attracts and retains talent while promoting the development and positioning of the city and the country in general. Distrito Tec´s objective is to improve the urban area and the quality of life of nearby communities (with over 26,333 residents). This includes offering open and renewed spaces, as well as access to different campus facilities and social programs.

The inherent challenges of the Monterrey campus´ transformation into a smart community represents the perfect opportunity for its students to develop the competencies needed to assess various real-life industrial and environmental problems and to understand key concepts of a Smart City [26]. This particular plan to use the Smart Campus concept as a learning mechanism for students within the Distrito Tec project is called the Campus City initiative. The main objectives of this initiative are: (1) to establish the idea among the student community that the campus is their home and that, as its citizens, it is their responsibility to take care of it; (2) to establish a relationship between the university's researchers and professional students to jointly develop solutions through the application of science, technology, engineering and mathematics (STEM); (3) to propose solutions that improve the citizens´ experience under the premise "society, planet, profit" (triple bottom line) through research, applied research, innovation and collaboration; and (4) to create a living laboratory (Challenge Living Lab) where teachers systematically identify, define and implement learning challenges based on the main problems that cities face. The Campus City initiative involves collaboration between the university's academic community, industries and the government, using Tecnologico de Monterrey's infrastructure of innovation laboratories to answer the main research question: how to promote a scalable Smart City framework that also provides a learning environment to engage and motivate students while helping them develop the necessary competencies to solve the smart community´s Pain Points through innovation.

Additionally, Tecnologico de Monterrey launched its new educational model "Tec21" in August 2019, with "Challenge-Based Learning" (CBL) as its central axis, where the definition and development of real-world challenges are used to guide and accelerate the learning process. Tec21 [27,28] is a unique and customizable model that promotes the development of competitive, competent individuals that can tackle any real-world challenge through research and innovation. This is catalyzed by inspiring professors who employ significant real-life challenges that motivate and engage students to create a memorable experience and trigger the learning process that is vital for their formation. Fundamentally, the Tec21 educational model could be described as a student-centered model characterized by four main components/pillars: (a) challenge-based learning, (b) flexibility, (c) highly trained and inspiring professors and, (d) memorable educational experiences [28–30]. All undergraduate programs at Tecnologico de Monterrey follow this disruptive model, which has been implemented in all 26 Tecnologico de Monterrey campuses with promising results regarding its implementation and the students´ learning experience [31–33].

Therefore, this work answers the need for a Smart Campus City framework which could be used as a base model to be scaled up and applied in a Smart City, while developing competent professionals prepared to face these challenges. Specifically, the main objectives of this work are: (1) to present an overall framework and methodology based on an innovation ecosystem that could be used to select the community's Pain Points; (2) to provide a dynamic platform in which Pain Points from the different verticals axes could be used as pedagogic opportunities to favor the development of competencies in an engineering syllabus; and (3) to present an example of the pedagogic design and implementation of a Campus City Challenge, while discussing the involvement of different stakeholders and the pedagogic learnings obtained from the experience.

This work is organized as follows:

- Section 2 introduces the Smart City´s main components, starting with the definition of the Smart City verticals, followed by the open innovation ecosystem on which the Campus City working model is based (including main stakeholders and step-by-step project selection process). Finally, the Challenge Living Lab´s objective and components are described; this is the methodology used to select real-world challenges with high pedagogic value.
- Section 3 presents an overall description of a Smart Energy challenge as an example of the Campus City Challenge Living Lab platform. This section starts with the pedagogic objective of the challenge followed by the pedagogic design. This includes the context of the challenge and how it was presented to the engineering students. Moreover, the challenge solution methodology and results/discussion are presented.
- Section 4 presents the overall findings and learnings regarding the implementation of the Campus City Challenge Living Lab from the perspective of the external stakeholders, the professors (pedagogic perspective) and the students.
- Finally, Section 5 presents the overall conclusions of this work, limitations and future work.

2. Campus City Initiative Main Components

2.1. Smart City Verticals: Smart Mobility, Water and Energy Definitions

Mobility, Energy and Water are the main vertical axes of a smart city, united under a common premise: reducing economic and environmental costs, and saving time through the use of data, information and telecommunication. The citizens' quality of life and their perception of the city they live in will improve through intelligent systems that can optimize the administration of resources and inform them about the status and availability of mobility, water and energy resources.

Smart Mobility—a series of initiatives, policies and actions whose main objective is to promote cleaner, safer and more efficient forms of transportation and to facilitate mobility via public or private transportation throughout the city.

Smart Water—the use of data acquisition systems, prediction and cognition models, as well as information systems to allow better decision-making by the users and the water infrastructure agency in terms of its accumulation, monitoring, distribution and traceability.

Smart Energy—to achieve a transition towards greater balance in the distribution and use of energy from renewable sources (sun and wind among others) and fossil fuels, with the purpose of polluting less and improving energy consumption through the use of environmentally friendly and safer technologies.

2.2. Open Innovation Ecosystem

An open innovation ecosystem is fundamental for delivering high-quality service. This is facilitated by the interconnectedness of different technological platforms, services and providers [4]. The Campus City initiative is based on this model of open innovation (shown in Figure 2). The value proposition of this initiative is to offer challenges that are relevant to the Tec21 model and to create high-impact innovation projects for the industry and the community. This could be achieved through the implementation of the academic innovation platform and using Distrito Tec as a Challenge Living Lab (described in Section 2.3).

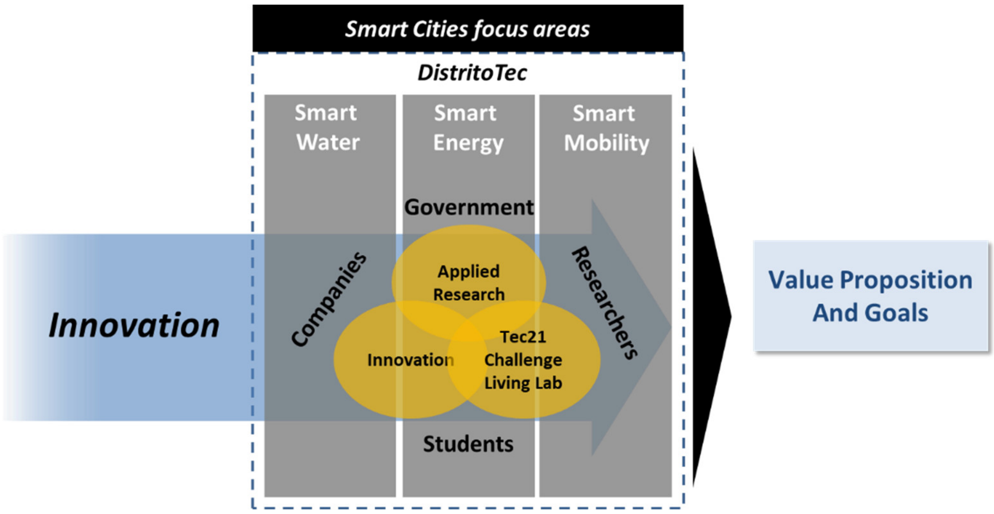

Figure 2. Campus City initiative general innovation model.

The Campus City initiative was designed to achieve the following goals:

1. Tec21 challenges
   - Identification and design of meaningful challenges that support our learning model.
   - Strong involvement of the Academic Community (lecturers, students, researchers, collaborators).
2. Industry-community innovation projects
   - Increased competitiveness through technology development to solve the requested Pain Points.
   - Creation of new businesses through the implementation of disruptive technologies.
   - Creation of high-social impact technologies, which reduce or eliminate major community challenges.
3. Applied Research Projects
   - Development of applied research to close the science-technology gap and solve complex challenges for industry and the community.

These goals are focused on the three Campus City verticals (Smart Water, Smart Energy and Smart Mobility) affecting the entirety of the Distrito Tec infrastructure, as shown in Figure 2. These three verticals will dictate the focus of the project and if a project does not comply with the objectives of one of the three main verticals, then the project is rejected. This strategy allows a better allocation of efforts and resources, increasing the chance of success.

The Campus City initiative working model is shown in Figure 3. This working model comprises three major stages: value discovery, execution and tech transfer. Throughout these stages, two main groups of actors have been defined to guide the initiatives. The first main actor corresponds to the stakeholders, in this case the industry, academia (campus) and government (top horizontal axis in Figure 3). The stakeholders provide problems and challenges from their specific sector. In this sense, the stakeholders can be considered as the Market Pull. The second main actor is the Campus City core team from Tecnologico the Monterrey, which includes the innovation area, steering committee, post-docs, partner professors and students (bottom horizontal axis in Figure 3). The Campus City core team offers the Technology Push. Information will flow between these two main groups of actors throughout the different steps or processes, allowing all parties to reach a consensus on the challenges to be solved.

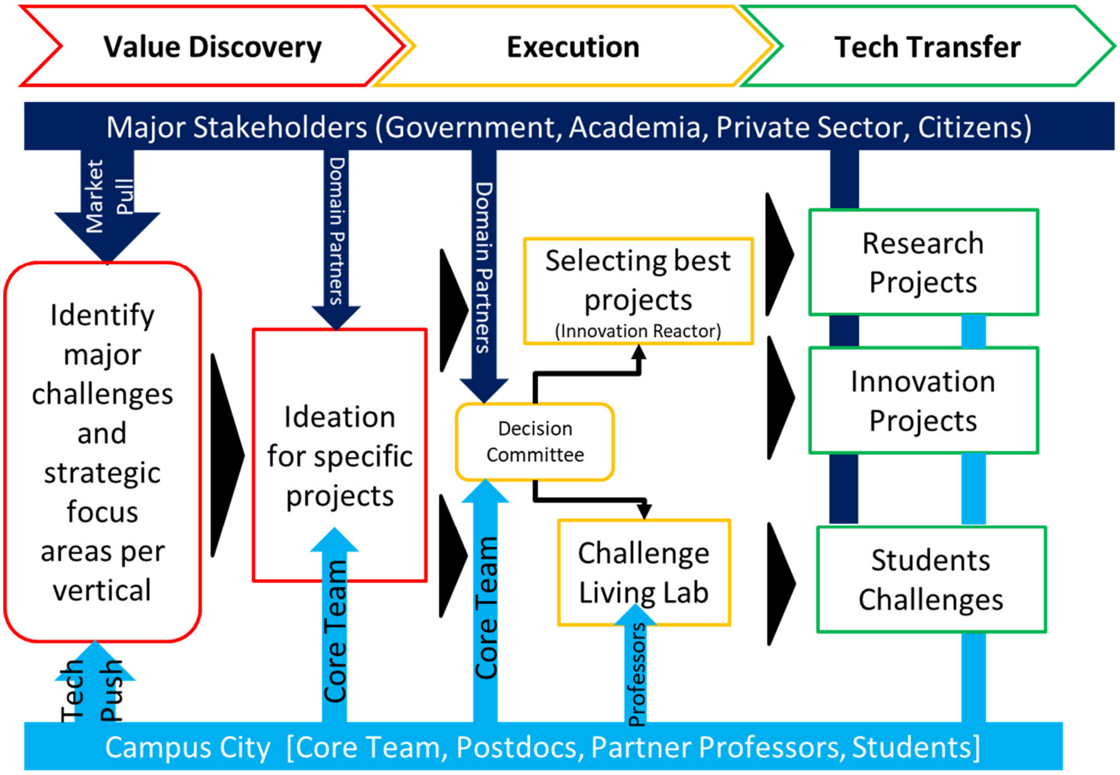

Figure 3. Campus City working model.

Regarding the stakeholders in Figure 3, the industry refers to companies that are related to the production, consumption and distribution of water and energy resources, and to how people move around urban settings. These companies have already determined their strategies and technological roadmaps. They have their own research groups, but they are always on the lookout for highly disruptive external partners. The opportunity for universities lies in solving their current challenges from a disruptive perspective and identifying new challenges that they had not even imagined or thought of, complementing the blind spot that all companies develop. The government has designed and implemented public policy directives relating to water, energy and mobility. For this reason, the authorities must also contribute and make recommendations regarding the analysis and development of these technologies and solutions.

Moreover, government entities have been supporting the development of these solutions by:

1. Proposing solutions and providing feedback on the feasibility of the potential solutions, especially with regard to social aspects and political context.
2. Funding, not only through direct sponsoring but also through partnership in the search for financial support with third parties at national and international levels.
3. First-hand knowledge of the results obtained, favoring the transfer of solutions within government institutions for their future implementation on a larger scale or replication in other regions.
4. Facilitating the implementation of the proposed solutions by authorizing actions on territories of public use. For example, authorizing the installation of video cameras to monitor the flow of vehicles on public roads.

The accompaniment of government entities, through the previous concrete actions, has encouraged students and researchers in the search for solutions to the country's problems under the Campus City initiative.

As mentioned above, the stakeholders and the core team will manage and implement different processes to reach an agreement on which challenges could meet the Campus City goals. This four-step process is described below.

Step #1: Identifying the main challenges, priorities and strategic focuses in each area.

Step #2: Breaking down the large problems into strategic problem areas that require the development of specific technological solutions and identifying a list of projects that are of common interest. Step 1 and 2 should be revisited and discussed once a year by the stakeholders and the core team.

Step #3: Obtaining and evaluating input from both internal and external stakeholders to select the best projects, those with a higher priority and that deserve the allocation of resources.

Step #4: Separating the specific problems into innovation, applied research, and Tec21 challenges. The Decision Committee, formed by the Campus City core team, analyzes the ideas that qualify to become projects, classifies them into innovation projects or applied research projects, and determines which problems could be introduced as Tec21 challenges.

Once those projects are identified and classified, they are assigned resources, researchers/professors, students, etc. in order to be executed and verified. The intention is for these projects is to end up as a functional prototype proven on Campus City (in the field). Moreover, the goal is to innovate, and innovation is achieved when the technological development is adopted by a user or a market, thus transforming science and technology into a profitable solution (recognition). In innovation it is important to stay focused and to be able to act fast. Therefore, the above-mentioned steps are distributed into three main categories to manage this innovation (Figure 3): (1) value discovery (or the discovery of the opportunity), (2) the execution, and (3) the technological transfer towards the final users or clients.

The ideas selected for Tec21 from the project list are sent to the Challenge Living Lab (Section 2.3) where these challenges will be transformed into suitable projects for classes. This transformation requires a methodology that complies with certain pedagogical aspects. After going through the Challenge Living Lab, the projects can be released as challenges that are executable by the students.

2.3. Challenge Living Lab

The Challenge Living Lab is a platform through which a problem is proposed and continuously developed as part of a project selected by the stakeholders and the core team. These projects must have a high social and pedagogic impact because the students' motivation increases when they are involved in projects where the knowledge learned has a meaningful purpose [34–36]. Moreover, this platform is key for the development of a Smart Campus, since it introduces or develops different technologies in an educational environment [25].

The main objectives of the Challenge Living Lab are systematic innovation, promotion of research efforts, formation of leaders, interconnectivity/data use and fostering multidisciplinary cooperation between public and private institutions with society. This includes a multidisciplinary communication effort between different institutions (university-companies) that provides information, data, technological, economical and human resources and different methodologies needed to promote research ventures that deal with different Pain Points. Moreover, the Challenge Living Lab strengthens and synergistically combines with Tecnologico de Monterrey's academic programs; that is, the students are actively involved in different learning environments that lead to the development of solutions for the problems being experienced by the community, companies or campus users. This involves close cooperation between these stakeholders and collaboration with colleagues to develop socially responsible ventures [34]. To achieve this, Campus City can be integrated into the Tecnologico de Monterrey's educational programs. Figure 4 illustrates the stages of the Challenge Living Lab, as well as the Challenge Based Learning pedagogic model.

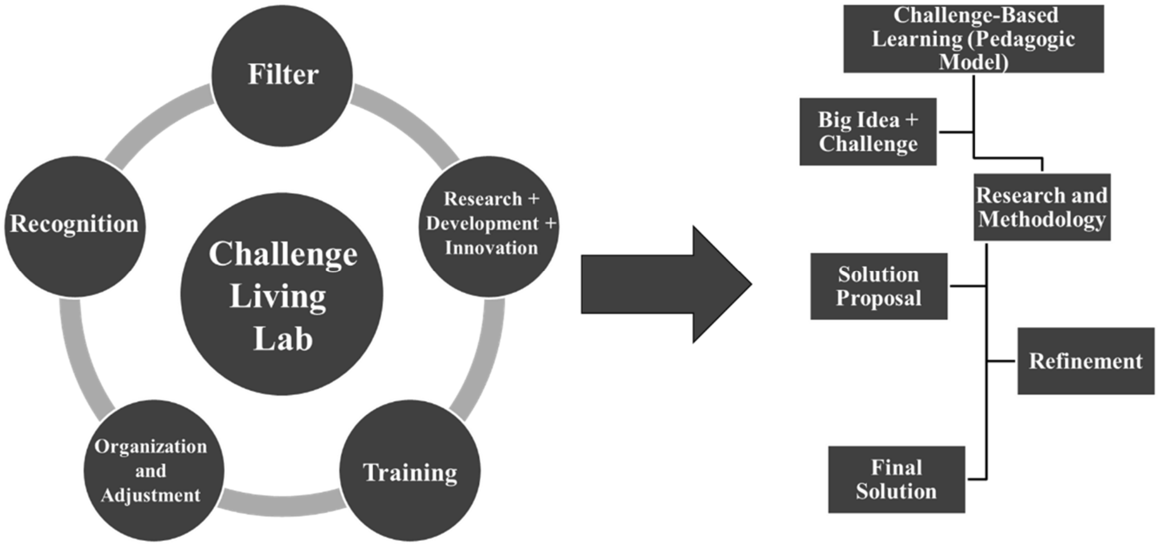

Figure 4. Campus City Challenge Living Lab virtuous loop and Challenge-Based Learning pedagogic methodology.

The Challenge Living Lab's virtuous loop consists of different components (Figure 4) that synergistically work towards the development of a pedagogic challenge based on the sustainable problems of the community, in this case the university district. The first component, Filter, refers to the selection of a project or challenge from both a technical-economic feasibility and cost-effective perspective, while considering the project's main impact on the different Campus City verticals. The second component, Research-Development-Innovation, denotes the availability of the technological and human resources to address the selected challenges. Within this component, different research groups and students are selected to address the challenge. The third component, Training, refers to the formative aspect of the challenge; that is, the challenge becomes a means for the development of competencies and skills in students. This component is naturally aligned with the objectives of Tecnologico de Monterrey's Tec21 educational model. Organization and Adjustment denotes the continuous improvement of the model based on feedback from the stakeholders and students. This component allows the documentation of the challenges, their successes and their areas of opportunity. Finally, Recognition refers to acknowledging the participation of all the parties involved.

As mentioned above, Challenge-Based Learning becomes the fundamental pedagogic approach for Campus City project. CBL focuses on the development on competencies as well as hard and soft-skills required to solve the Pain Points of a community or stakeholder [34,37–39] within an innovative and flexible learning environment [34,40,41]. Combined with Flipped Classroom techniques, this pedagogic approach promotes high levels of engagement and motivation within the students since they develop a sense of meaningful purpose through the learning process [34].

The following section describes in detail the challenge obtained from the above-mentioned process for the Smart Energy vertical axis as an example of the structure, pedagogic intentions and objectives of a typical challenge under the Campus City project. This description includes the overall objectives of the challenge, the pedagogic intentions and methodology followed by the students. For Smart Mobility and Smart Water, a brief description of the challenge and their components (stakeholders, methodology and objectives) could be found in the Supplementary Material Document S1 (Figures S1 and S2) [41–46]. Finally, Section 4 presents an overall discussion on the learnings and results.

3. Campus City Challenge—Smart Energy

3.1. Smart Energy Challenge—Smart Classrooms for the Post-COVID Era

The pedagogic objective of this challenge is to engage students in the topic of energy consumption in buildings and the operation of heating and ventilation air conditioning (HVAC) systems. Since the operation of HVAC systems is the main source of energy consumption in buildings, this challenge looks for alternatives to minimize this energy consumption and possibly transform new and existing buildings into buildings with net zero energy consumption. External partners involved in the challenge were Distrito Tec and the Managing divisions related to physical infrastructure of Tecnologico de Monterrey (maintenance/physical plant department).

3.2. Pedagogic Design

The objective of the fall 2019 and spring 2020 Smart Energy Challenge, was to verify that randomly selected classrooms at Tecnologico de Monterrey satisfy these requirements for air quality and thermal comfort, and to propose strategies to achieve this at the lowest energy cost in preparation for the return to in-person activities following the COVID-19 pandemic. The challenge required that the students search for the regulations of the specific case, the required instrumentation and, if necessary, its manufacturer. Moreover, the students were asked to implement a detailed plan to generate a baseline, and to compile a database of the rooms´ conditions in terms of temperature, humidity and CO_2 concentrations. Finally, with the obtained data and its analysis, the students were asked to propose solutions, considering energy efficiency aspects in conjunction with other aspects, such as thermal comfort and air quality.

An overview of the Smart Energy challenge is shown on Figure 5. The big idea behind the challenge corresponds to the need for decreasing energy consumption in buildings while simultaneously meeting with the comfort needs of their occupants. Students were asked to propose strategies to accomplish this purpose.

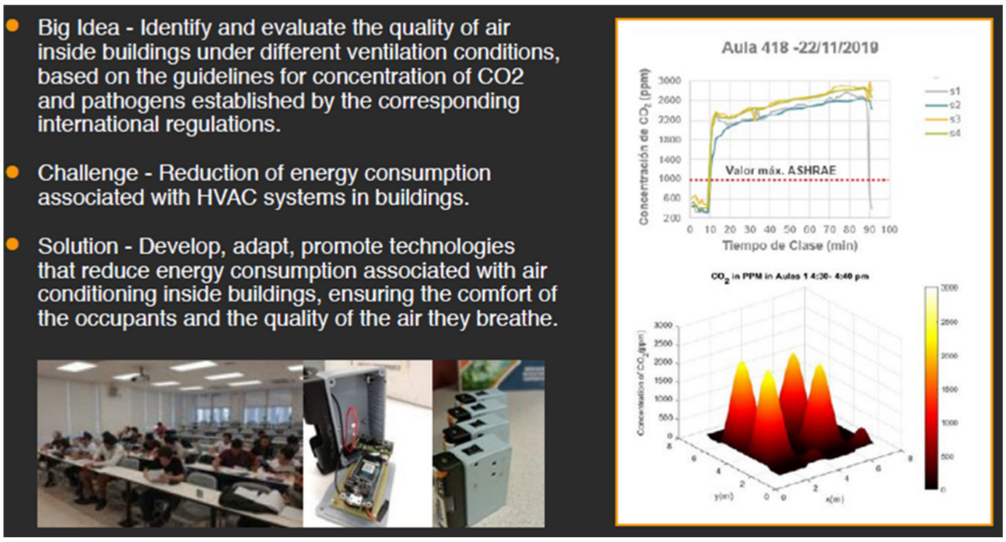

Figure 5. Use of low-cost sensors to monitor CO_2 concentration in classrooms.

An example of the challenge introduction or motivation for the students is presented below.

"In 1982, the WHO defined the sick building syndrome as a set of annoyances and diseases caused, among others, by poor ventilation and temperature decompensation, where at least 20% of the people inside the building feel unwell. More than 30% of the buildings that surround us could cause permanent discomfort to their occupants. If one of its occupants suffers from asthma, allergies, or has respiratory problems, these could be aggravated. The number of bacteria and viruses could increase, even increasing this increases the probability of becoming infected with COVID-19. Reducing the CO_2 concentration from 2000 ppm to 1000 ppm increases human efficiency by

12% and reduces the possibility of making mistakes by 3%. It is urgent to increase awareness of the importance of indoor air quality and generate real, high-impact alternatives to improve it in Tec's classrooms.

People currently spend 90% of their time indoors (homes, workplaces, offices, schools, hospitals, factories, or even shopping centers) [47,48]. *Therefore, it is necessary to provide satisfactory indoor air quality while guaranteeing the energy-efficiency of the buildings. A healthy environment could be favored by having an adequate Indoor Air Quality (IAQ) level and ventilation system. Airborne virus and bacteria transmission is favored as a result of having poor IAQ, which could generate different health problems* [48].

The main aspects that influence air quality are vehicle traffic, fuel burning, industries [47,49,50], *and the low performance of air conditioning systems (HVAC)* [51]. *Carbon dioxide (CO_2) from indoor air is one of the critical factors in determining IAQ* [47,52–55]. *In the outside ambient air, CO_2 varies typically between 250 ppm and 350 ppm. The CO_2 in the indoor air must be below 1000 ppm to avoiding negative impacts on the occupant's health* [48,56,57].

Several works have focused on assessing air ventilation on office buildings. However, not enough attention has been paid to school buildings [58]. *A classroom is a tight space with several people inside, therefore, the air quality can deteriorate over time* [50]. *Students comfort, health and productivity (learning efficiency and attention during classes) could be dependent of the IAQ. This includes a decrease in students' performance, spread of viruses such as SARS-CoV-2* [52] *and different social and economic repercussions* [49,59]. *The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends to increase natural ventilation, improve central air filtration or other HVAC systems that can be operated for extended hours (24/7 if possible), and the use portable HEPA purifiers. Moreover, having acceptable concentration values of CO_2 (at levels established by regulations) ensure the comfort level of the occupants and efficient energy consumption* [60].

The objective of the smart energy challenge presented to the student is the following:

"Evaluate the indoor air quality under different ventilation conditions according to international regulatory standards and assessing CO_2 concentrations. Offer proposals to improve the air quality in classrooms as well as energy savings."

3.3. Challenge Methodology

Students were provided with a general strategy as a guide or methodology. The strategy involved four steps described in the following subsection, including a brief example of the information that would be expected from the students (text in italic format).

3.3.1. Step 1—Study Case 3

The first stage is the definition of the boundary conditions required to solve the challenge. Moreover, the students are required to define the type and number of study rooms, the location of the study, the scenario in which they will carry out measurements and analysis, as well as the specific identification of the energy system to be studied.

Example of obtained result: "In this work, we analyze two classrooms classified as non-residential buildings located at the Tecnologico de Monterrey, Campus Monterrey, Mexico. These classrooms correspond to the buildings A and B, both with northwest orientation, the number of occupants per class is 15 and 25, respectively. The installed HVAC systems have a constant evaporator and enthalpy, are kept continuously in operation to maintain the comfort of the occupants when modulating the equipment injection."

3.3.2. Step 2—Instrumentation

In this step, the students must list how they intend to monitor current conditions to determine the baseline to be compared with ideal situations.

Example of obtained result: "Particle devices, Xenon, and Boron modules were used. Through a communication protocol I2C and the SCD30 sensor, real-time monitoring of the CO_2 concentration (ppm), temperature, and relative humidity of the classrooms will be performed."

3.3.3. Step 3—Monitoring Campaign

The students are advised to carry out a monitoring campaign, using the proposed instrumentation while considering the moment, duration, location and number of the monitoring instruments and the frequency of data acquisition to construct the baseline. It is worth noting that the students must justify each decision and assumption made based on the literature available.

Example of obtained result: "Case A was monitored on November 15 and 22, 2019, for 100 min from 08:30 to 10:10 a.m. The monitoring time for Case B was 90 min, on November 12, 22, and 26, from 4:05 to 5:35 p.m. The placement of sensors varies, depending on the number of occupants and the size of the classrooms. An SD card incorporated into the Boron module was used to collect the data in real-time. Data were captured every 10 s."

3.3.4. Step 4—Evaluation

Finally, from the data collected, the students need to consider the aspects necessary for its evaluation, such as calculations and regulations, and to investigate the necessary basic theory and numerical methods to obtain a baseline while comparing it with the specifications of the regulations.

Example of obtained result: "In the last stage, the analysis of the CO_2 concentration data was made, the results of both cases were verified with the international standards, ASHRAE 62 and 62.1, ASTM D6245-12 [56,57,61]. *Besides, some actions were designed that could be implemented to improve IAQ. CO_2 concentration values, occupancy of 25 people, and the dimensions of the classroom were used to calculate the ventilation requirements per person. This number was compared with the ASHRAE 62 standard."*

From the development of these four steps, it is expected that the students will develop and apply the concepts, knowledge, and skills that correspond to their academic program. For example:

- To know the operation of adequate instrumentation for the current evaluation of the classrooms. For example, temperature, humidity, lighting, and CO_2 sensors.
- To design experiments, sampling, and statistics to obtain valid measurements for obtaining results.
- To make decisions about the placement of the sensors for representative data collection.
- The use of software such as Matlab®, to simulate the current and ideal conditions of the classrooms, using their different measurements.
- To access databases and information to obtain and perform the necessary data processing calculations. For example, calculating the volume of air per second that the room must have, ventilation level, comparison values for air quality, and comfort levels.

However, some assumptions and simplifications may be necessary to conduct the challenge. Specifically, the degrees of freedom must be clear, the type of sensors that are available (provide them with the sensors and guide them in obtaining the measurements), provide information regarding the study system, for example, current HVAC models and features in classrooms. Finally, the student must be provided with information on the available hours and the policies for the use of the rooms and the scope of the project.

No physical risks are expected from this challenge. Nevertheless, there is a risk that students will not adequately define the situation or the scope of the project. For example, to be aware of external factors that may affect their results or their proposals, such as the physical conditions of the city where they are conducting the study, meteorological conditions (temperature, humidity profiles), classroom characteristics (number of windows, dimensions, materials), description of the air conditioning system, georeferencing, etc. Thus, the professor must play an essential role in guiding the students with questions that may motivate them to make more in-depth insights into the solutions that they are proposing, in order to help them to develop the desired competencies.

3.4. Challenge Implementation Results

The challenge was implemented during August 2019–June 2020. A team consisting of three 9th-semester Mechanical Engineering students was assigned to solve the Smart Energy challenge. Some results of the challenge and the student experience from the teacher's perspective are discussed below.

Figure 6 shows that the students were able to obtain data through low-cost sensors. However, they did not demonstrate the same ability in the use of Matlab® to interpolate the conditions at points where there was no sampling, nor the use of scales to demonstrate a real behavior of CO_2 concentration. During the challenge, it was noted that the students struggled to use the mathematical equation to calculate the number of room air changes necessary to maintain the CO_2 concentration at acceptable levels, according to regulations. However, they demonstrated competency in database consulting.

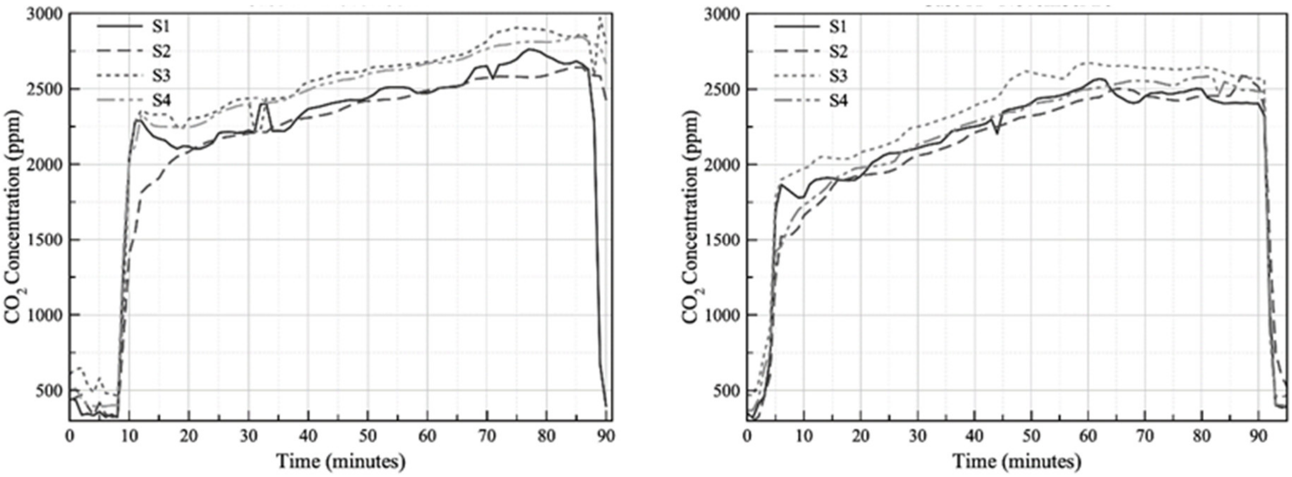

Figure 6. CO_2 concentration profile in two classrooms at Tecnologico de Monterrey.

An excerpt of the students' conclusions is presented below:

"Inexpensive sensors were used to perform classroom measurements that measure CO_2 concentration, temperature, and percentage of humidity within the classroom. According to the data obtained, color maps were constructed in Matlab® to visualize the CO_2 concentration during a class session. The concentration of CO_2 remains over 2000 ppm, reaching a peak value of up to 2883 ppm in the afternoon, which is well above the limit recomended by the regulations that tell us the standard of 1000 ppm."

"Likewise, calculations of the liters of air per second that each person should have in the room were made. Taking into account an average concentration from outside such as 400 ppm, the highest amount of CO_2 concentration, and the variable found with the average weight and height of a Mexican, we obtain 2.17 L per second for each person, being well below what gives us the regulation of 5 L per second per person."

"The air quality inside the classrooms of the Tecnologico de Monterrey is not adequate to ensure the well-being of its occupants. For this reason, it is proposed that installed air conditioners achieve adequate ventilation so that students and teachers have the security that they will stay healthy and that academic performance increases. Likewise, a filter system in the air conditioners capable of eliminating viruses is necessary to avoid contingencies such as COVID. In this way, students and teachers will feel protected by the Institution since the necessary hygiene measures will be taken to eliminate any virus."

The COVID-19 Pandemic affected the normal development of the Smart Energy Challenge since by the middle of spring 2020 students could not get access to the campus and therefore, they could not obtain new data. This fact affected their motivation, and their achievements were much lower compared to the students that had participated in the previous semester (fall 2019).

3.5. Discussion on the Challenge Implementation and Results

The students made fair use of the instrumentation that was available to them. They also designed and manufactured an interconnected system of low-cost sensors to obtain CO_2 concentration, temperature, and humidity data in the cloud. In addition, they compared this data with the recommended values defined by international organizations.

It was observed that students focused on CO_2 concentrations, while their analysis does not take into account temperatures or humidity concentrations, and gave more value to the health aspect than to the energy aspect. This situation was expected, since the challenge had double goals, which in this case was not only to propose alternatives to improve indoor air quality but also to validate the energy efficiency of these solutions. One possible explanation for the student' performance could be that the time available for the challenge was not enough, nor was the emphasis given to specific topics such as sensors and not energy aspects. This is an area of opportunity for the present challenge.

In terms of motivation, the students appeared to be encouraged and willing to show their results to share the importance of making improvements in the ventilation of the classrooms. Proof of that was submitting their work to the *Conexión Tec* contest. It is carried out every semester organized by Tecnologico de Monterrey to connect students and industry through their classroom projects. In the next version of this challenge, designers will include tools to evaluate the effect of the challenge on the students´ engagement on the proposed topics. Finally, from the technology side, students demonstrated that the classrooms that they monitored had problems in their HVAC system and that those problems affect students' performance and will limit the use of these classrooms in the post-COVID era. Future challenges will focus on providing alternative solutions for Tecnologico de Monterrey administrators.

The following section presents the overall findings and learnings of the implementation of the Campus City and Challenge Living Lab framework. This includes the stakeholders perspective and involvement, as well as the perspectives from the professors and students that carried out the challenges.

4. Findings and Learning

4.1. Stakeholder's Perspective

A city's Pain Points, defined from the citizens' point of view, lead to new ideas for solutions. The goal of Campus City is to activate the Smart City ecosystem, where the private sector, the government and academia interact to solve contemporary needs. The Challenge Living Lab enables the students to better comprehend and participate in this interaction by playing an active role in developing innovative solutions to those Pain Points. In the Smart Mobility Challenge, the stakeholder shared a first approximation of energy requirement computation as well as a driving cycle from a local urban zone. The main contributions of the industrial stakeholder were: (a) their experience and coaching on vehicle dynamics, (b) their approach to projects in an industrial context, where the focus is on economically sustainable results, and (c) their openness to create new trusted relationships with our university based on these challenges, and to explore new projects based on these results.

In each challenge, the participation of an external mentor (their point of view, experience, and innovation focus), the students (their need to learn how to apply theoretical knowledge to solve real-life challenges) and the professor (their guidance, tutoring and accompaniment) creates an ecosystem of interaction, leadership, application of knowledge and follow up.

The different stakeholders had three main roles during the challenges presented: (1) to provide problems and aid in the selection process; (2) to co-design the challenge; (3) to mentor the students while providing information/data/experience to enrich the students´ learning experience. The stakeholder plays an important educational role, acting as a link between the students' theoretical and academic environment and the arena of practical and real-world experience. Thus, the stakeholder acts as both mentor and client.

For instance, the maintenance/physical plant department, specifically the HVAC team, was the main stakeholder and co-designer in the Smart Energy Challenge. Initially, the challenge was developed by the academic advisor (professor) and then presented to the HVAC team for their inputs and suggestions. This was a crucial step since the HVAC team provided the students with critical information on the current ventilation and air conditioning system. The students constantly reported their advances to their academic mentor and to the HVAC team to receive feedback, adjusting their calculations and models to meet necessary international regulations and standards (ASHRAE 62 and 62.1, ASTM D6245-12). The results obtained, reinforced by the students-stakeholder interaction, led to the conclusion that the currently operation HVAC system does not meet the values required by the international standards. Consequently, the maintenance/physical plant department designed a strategy that avoids internal air circulation in the classroom while installing specialized air filters in the HVAC system.

For the Smart Water Challenge, an international academic stakeholder contributed to the co-design of the challenge. Their main contribution during the screening of the Pain Points and challenge design was to focus the study on emerging water pollutants, such as the per- and polyfluoroalkyl substances (PFAS). Moreover, the following challenge objectives were developed between the academic advisor and stakeholder:

1. To understand the environmental threats of chemicals derived from PFAs.
2. To understand the sources of PFAs and why they are found in drinking water.
3. To explore guidelines, government regulations, and action plans for significant concentrations of PFAs.
4. To survey data and trends to recognize concentrations that pose potential health hazards.
5. To develop corrective solutions in cities based on existing data, considering the implementation of various technologies and their respective costs.

Similar to the Smart Energy Challenge, the Smart Water Challenge stakeholder was actively involved with the students, providing guidance and mentorship throughout the challenge; this included an introductory lecture on the history of civil and environmental engineering. The Smart Mobility Challenge stakeholder's contribution to the academic environment was the context of actual practice in automotive engineering and the executive focus on generating technically sound solutions in record time.

The Challenge Living Lab framework contributed to building trust between stakeholders, the creation of academia-industry relationship, and the exploration of future projects (sponsored research). After the end of the course, the external partners (government, private sector and/or citizens) mentioned new ideas for future challenges in the next academic periods, thus beginning the virtuous-loop of the Challenge Living Lab and opening the possibility for further applied research projects.

4.2. Pedagogic Perspective

Students reported feeling more engaged with the syllabus content after the conclusion of the challenge. Additionally, students strengthened their understanding of different concepts, competencies and skills by systematically presenting, reporting and discussing their results to the different stakeholders. This interaction prepares the students for a real-world situation in which different points of view (citizens, academia, government, industries) contribute to the development of solutions. In a similar manner, students mentioned they enjoyed seeing real-life situations from different perspectives, learning new skills and tools, reviewing the concepts learned in class in a more practical hands-on manner, and acquiring experience in real-life problem solving.

However, it was also observed that despite the students' motivation and creativity, they initially require step-by-step directions on the activities that they should perform to solve the challenge, especially in challenges that involve experimental work.

The learnings, advantages and disadvantages of the Challenge Living Lab and challenge implementation are presented in Table 1.

Table 1. Campus City Challenge Living Lab learnings, advantages and disadvantages.

Learnings	Advantages	Disadvantages
1. The students are sensitized to actual real-world challenges and respond quickly to the smart city ecosystem's need for solutions.	1. The participation of government and private sector provides "real-world experience" for students.	1. Real world challenges sometimes are very focused on specific components of the full syllabus, so it is complex to evaluate course knowledge with one big challenge.
2. The students feel more confident in an industrial environment as they develop their competences.	2. The challenge structure in combination with nano/micro-challenges reinforces the students' critical thinking competency (systematic methodology).	2. The duration of the big challenge mostly is not enough to achieve and apply deep knowledge (this varies according to the students).
3. The syllabus is more advanced than required by regional industries.	3. The government and private sector take advantage of their involvement by recruiting talented students.	3. The students require intensive guidance (step-by-step instructions) at the beginning of the challenge.
4. The framework motivates the private sector to try new ideas.	4. The challenge fosters research and innovation.	4. The projects tend to be ambitious for the course duration.
5. The dimension and scope of the challenges must include at least 80% of the syllabus in order to engage students.	5. The challenge provides the students with a high-responsibility active role.	
6. The field validation of solutions is required in order to achieve the goal of the challenge.	6. The students are engaged and motivated throughout the challenge.	
7. The micro-challenge contents must lead up to the big challenges, rather than being independent from them.		
8. The multidisciplinary mentors enrich the framework, the challenge and the students' experience.		

5. Conclusions

The main contribution of this work is to present the overall framework of Distrito Tec's Campus City project that includes an open innovation ecosystem and the Challenge Living Lab as a platform for the identification of high-socially meaningful projects that could be used as a pedagogic opportunity for the development of competencies needed to solve different community-industrial-governmental Pain Points.

It is concluded that Distrito Tec's Campus City is an ambitious initiative that aims to provide the industry, government, academia and especially the community with innovative and smart solutions to the current high impact and complex Water, Energy and Mobility problems. The Campus City open innovation ecosystem allows the identification of these highly relevant challenges that could be solved through the use or design of disruptive technology. By solving these challenges, the wellness of the community and the efficient use of resources could be achieved.

Consequently, the Challenge Living Lab is highly relevant as the selected challenge provides the ideal pedagogic framework for the students to develop different competencies and skills that they will require throughout their professional life while fostering the identification and solution of highly relevant problems for the community, industry, government and academia.

Moreover, Challenge Living Lab platform opens the possibility for international and multidisciplinary projects and collaboration with different research institutions and governments. For instance, different challenges from the Challenge Living Lab, Smart Mobility vertical were tested in a pilot program as a "4.0 Energy Harvest Challenge" with the Indian Institute of Technology, Kharagpur. Students engage in a design challenge for different interconnected technologies for energy harvesting. More research is needed to scale-up this program to other institutions and include different common problems for the institutions/communities involved, which could generate logistical problems among faculty and students.

The scope of this work is defined within the Distrito Tec transformation initiative, in which the Tecnologico de Monterrey university, the surrounding Community, the Municipal

Authorities and Private Companies are committed to generate an urban transformation that inspires other districts and cities to undertake continuous transformation to improve their Quality of Life. However, the Distrito Tec projects and their implementation depend on the willingness, commitments and agreements between the community and the municipal authorities. This represents a challenge, because the Distrito Tec project has a horizon of 15 years during which the renewal of municipal authorities will take place several times, disrupting the continuity of the project. Therefore, the active involvement of the academia through Campus City projects could play an important role as a catalyst that constantly provides solutions, technology, and human resources to keep track of those agreements and aid in the continuity of the Distrito Tec project despite government transitions.

Future work should address: (1) the scaling up of the proposed framework into a model that could integrate different sectors, stakeholders, and communities, (2) follow-up and implementation, on a city-level or industrial scale, of the proposed challenges' solutions based on interconnected technology and (3) the evolution of the socio-cultural impact and Quality of Life by the implementation of the Campus City project (triple bottom line, people-planet-profit).

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app112311085/s1, Figure S1. Flow diagram of the overall methodology for the smart; Figure S2. Objectives and tasks to be completed for the Sustainable Water II course challenge mobility challenge. nCh and mCH refers to the nano-challenge and micro-challenge, respectively.

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