2022

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sustainability

Article

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Abstract: Creating a more sustainable world will require a coordinated effort to address the rise of social, economic, and environmental concerns resulting from the continuous growth of cities. Supporting planners with tools to address them is pivotal, and sustainability is one of the main objectives. Modeling and simulation augmenting digital twins can play an important role to implement these tools. Although various green best practices have been utilized over time and there are related attempts at measuring green success, works in the published literature tend to focus on addressing a single problem (e.g., energy efficiency), and a comprehensive approach that takes the multiple facets of sustainable urban planning into consideration has not yet been identified. This paper begins with a review of recent research efforts in green metrics and digital twins. This leads to developing an approach that evaluates organizational green best practices to derive metrics, which are used for computational decision support by digital twins. Furthermore, it leverages these research results and proposes a metric-driven framework for sustainability planning that understands a city as a sociotechnical complex system. Such a framework allows the practitioner to take advantage of recent developments and provides computational decision support for the complex challenge of sustainability planning at the various levels of urban planning and governance.

Keywords: digital twin; green policy metrics; simulation; smart city; sustainability

Citation: Corrado, C.R.; DeLong, S.M.; Holt, E.G.; Hua, E.Y.; Tolk, A. Combining Green Metrics and Digital Twins for Sustainability Planning and Governance of Smart Buildings and Cities. *Sustainability* **2022**, *14*, 12988. https://doi.org/10.3390/su142012988

Academic Editor: Mamadou K. Traoré

Received: 23 August 2022
Accepted: 6 October 2022
Published: 11 October 2022

1. Introduction

Modern cities are complex systems with social, economic, and environmental challenges being interwoven in often nonlinear relations, often including feedback loops. Effects are sometimes delayed and can be perceived as decoupled from their origin. Observed effects also may be the superimposed effects of multiple origins. Furthermore, outcomes may have multiple side effects. This makes the application of performance measures complex as well, requiring computational model support for the planning and governance of such systems [1]. General examples for decision-making processes in complex systems and decision support system requirements are given in [2]. Within this paper, we propose the use of digital twins to support planners with a focus on sustainability.

Sustainability is becoming a topic of growing concern, especially for big cities. According to a recent study published in [3], approximately 75% of global CO_2 emissions are attributed to city emissions. Furthermore, more and more cities with large populations are coastal and are extremely vulnerable to possible sea-level rise in the decades ahead. All cities are vulnerable to urban heat island effects, which are detrimental to the health of the citizens, as exemplified in [4], but even when the focus is not on such extreme situations, focusing on sustainability planning and governance is a good practice to avoid wasting valuable resources.

Systems engineering developed the concept of digital twins in model-based engineering to support engineers in the design and governance of complex systems [5]. A physical twin, the system of interest, is accompanied by a virtual twin, a computer representation of all important aspects and behavior of the system which is often in the form of a software agent, such as described in [6]. Digital twins help support feasibility evaluation during the requirements analysis and initiation phase. Particularly, they allow conducting trade-off analyses and experiments without the need to have the actual system in operation. In the development phase, the virtual twin is used in support of specifications, helping to reduce ambiguities. In the operations and maintenance phase, the physical system is connected to the virtual representation through sensors so that the digital twin contains all the data that can be used to monitor and improve the physical counterpart in real time and through longitudinal analysis of the data [7]. The recently published reviews of digital twin potentials for cities [8,9] provide more detailed examples.

Many of the published examples, however, are focusing on the development and use of a digital twin to support a single-metric solution, such as optimizing the layout of production lines [10], wastewater management [11], vehicle maintenance [12], and more. All these solutions solve a particular problem. In this paper, we propose a framework that undertakes a holistic approach to studying multiple green metrics by leveraging the digital twins technology. Such a framework would allow several digital twin models to collaborate and contribute to solution classes while building a system of systems. Moreover, this framework provides support to the user in all tasks of interest (e.g., planning and implementation, operations and maintenance, expansion and evolution, etc.).

Our research identified two main challenges, both leading to a multi-scale, multi-attribute, multi-objective approach. The first challenge is that a city needs to be understood on several different layers that are interconnected by feedback loops and relations that may span over several layers, as described in [13]. Similar to other complex systems, applying reductionism is not helpful, as important interconnections cannot be understood and evaluated using this paradigm. Figure 1 shows the underlying concepts. A city is made up of heterogeneous blocks or neighborhoods, which often are as much defined by their social attributes as by their technical attributes. The potentially smart buildings have rooms in which devices are placed. The environment influences all, but there are additional interconnections, such as a building in a smart city, where power consumption needs to be reduced and the building utilizes the devices, either in competition or in alignment with room controls. While planners are not interested in providing smart devices, they are interested in the effects that can be discovered through the addition of smart devices.

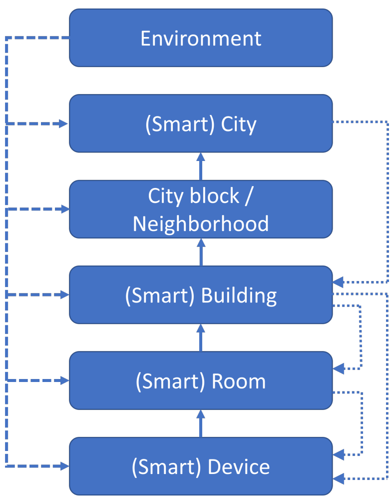

Figure 1. Conceptual layers of a city as a complex structure.

The second challenge is to provide realistic representations of the city and its components once the concept of the multi-scale, multi-attribute, multi-objective, complex, sociotechnical system is embraced. Figure 2 captures the idea schematically. On the left-hand side, the physical city is represented with its buildings, the supporting infrastructure, and its citizens. This is also where organizations and corporations are contributing to an important social aspect with the added technical sensors and derived metrics. On the right-hand side, the collection of digital twins provides the computational decision support needed for planning as well as governance. In the lower part of the figure, the interplay of important standards, metrics, and methods is shown. They are derived from green best practices and are applicable in the physical as well as in the digital world. All these concepts, including the standards mentioned in the figure, will be described in detail in the following sections.

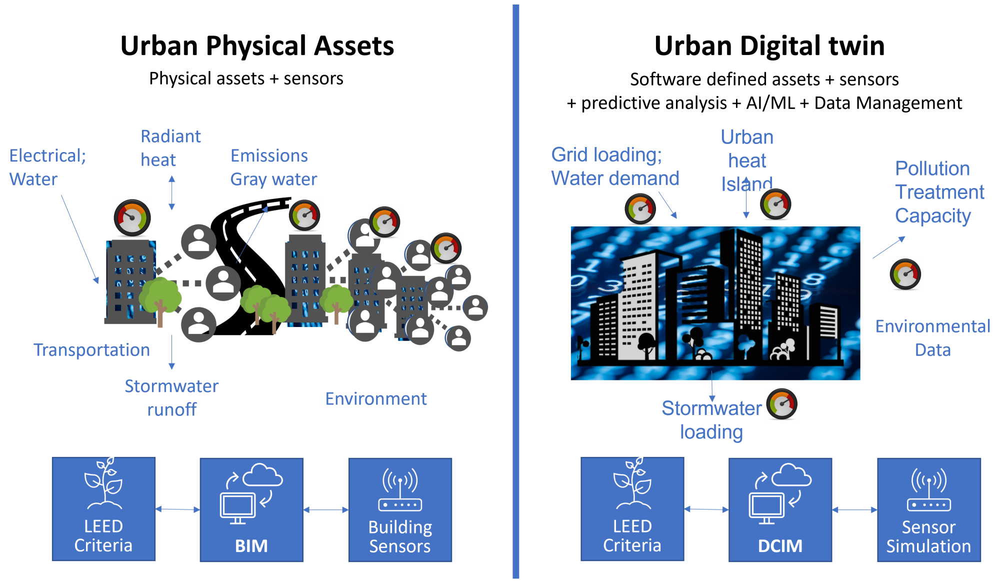

Figure 2. Conceptual layers of a city as a complex structure.

It is noteworthy that on the physical side of the diagram, sustainability has become essential for modern organizations to remain competitive in today's fast-paced economy. In many cases, sustainability decreases costs, increases safety and security, and supports employees' health [14]. In addition, being green has become more and more important for an organization's brand image, impacting talent recruitment as well as both employee and customer retention [15–17]. Despite the growing awareness and acceptance, however, there is no single, agreed-upon set of metrics to evaluate companies on sustainability practices. Such metrics are not only essential to track and compare organizations and their practices, but they also build the foundation for developing guidelines and regulations. Furthermore, we will show that common metrics are also essential for computational support provided by digital twins.

2. Methodology and Structure of the Contribution

This paper describes the necessary steps, with a focus on the need to align already ongoing efforts and applied solutions, to utilize digital twins to support analysis in sustainability planning with focus on smart buildings, or even cities. Figure 3 provides an overview of our applied methodology, which comprises three steps.

We start by using two systematic literature surveys conducted in earlier studies in the field of green metrics (1) [18] and a second one regarding simulation and sustainability (A) [19]. In our first step, we are focusing these earlier results of these surveys to provide a basis of articles applicable to measure sustainability in practical applications (2) and on articles focusing on digital twins (B), as described in the next paragraph. The second step is the identification of applicable metrics (3) and applicable digital twins (C), which are then combined into the proposed framework (FW) combining the two branches.

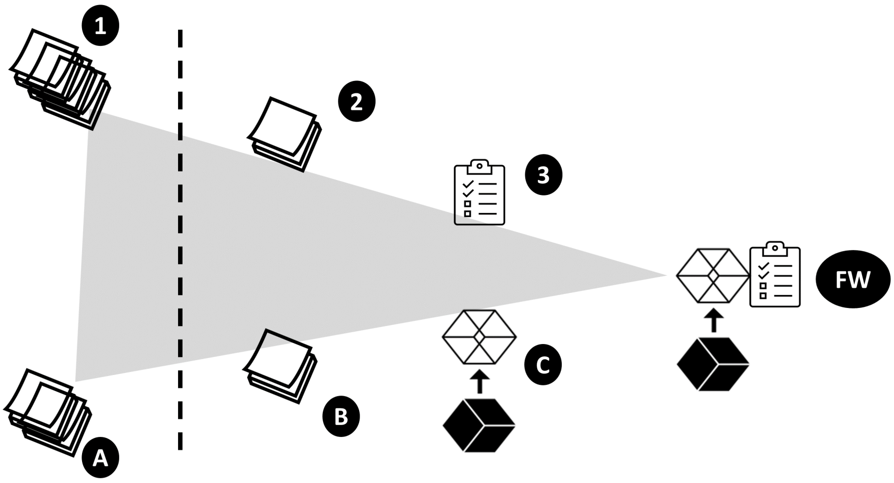

Figure 3. Applied methodology resulting in the proposed framework.

In detail, in Section 3, we present the main insights of a literature review to survey the sustainability efforts across the United States and identify leading industry best practices (2). These insights lead to the identification of the most promising metrics to address sustainability for systems and subsystems of interest to the planner. We use these metrics to collect feedback on their application and lessons learned from practitioners. From this literature survey and feedback, we demonstrate the need to develop metrics, including providing an example of an applicable real-world sustainability metric that is applied to certifying buildings and will also be used later for digital twins as well.

In Section 4, we provide the results of a complementary literature survey to lay the foundation for sustainability through studying digital twins (B). Particularly for so-called smart cities, the interconnection of all components was dealt with in [20], including addressing the challenge of sustainability on the conceptual level in [21,22]. The same ideas can be applied to sustainability planning, as smart devices and smart buildings contributing to smart cities often are accompanied by digital twins, but their application often seems to be in its infancy and confined to academic research laboratories. In this paper, these ideas will be extended, with an emphasis on sustainability. This extension includes some detailed examples, such as planning and operating data centers utilizing sustainable technology, as discussed in [23], but focusing on using digital twins [19].

In Section 5, we propose a conceptual framework to enable computational support for sustainability planners by bringing the various methods together. Use cases will exemplify the framework and its applicability and seek to address green best practice by taking a holistic approach of studying multiple green-related metrics by means of digital twins. The objective is to contribute to the standardization of concepts and terminologies while applying digital twins for sustainability planning. We give two use cases: First, the Sustainable Data Centers with focus on identification of applicable metrics ((3) in Figure 3), and second, the Technical University of Crete (TUC) "smart building" testbed that supports such a framework and that is represented as (C) in Figure 3. Further research in these two use cases leads to the development of a digital twin model that applies our ideas expressed in the proposed framework, depicted as (FW) in Figure 3.

This paper does not introduce new technologies. The innovation provides the context and current state of green best practice studies using digital twins. Previously, the focus was on mostly single-metric green best practice studies. Comparability of results is often difficult due to the lack of a centralized or standardized way of sustainability. There are lots of certifications, standards, and government guidelines that make the definition of "green best practice" elusive. Providing a conceptual framework allows the practitioner to take advantage of recent developments, thus allowing them to provide computational decision support for the complex challenge of sustainability planning at the various levels of urban planning and governance. The examples provided in Section 5 provide the necessary proof of feasibility to elevate the framework beyond the state of a pure conceptual proposal.

3. Defining the Metrics

To investigate the current state of "green", we leveraged a survey of the "state-of-the-art" of green practices and green policies across both government and industry [18]. This survey included reviews of government agency sustainability plans and published "green" goals, executive orders (EOs), and other legislation related to "green", as well as the timeline of when and how these documents were placed into effect. For industry, a survey of key players was identified based on multiple popular blog rankings in an effort to capture public sentiment on industry leaders in the field, as well as the company's documented award certifications. The publicly released sustainability plans and practices of these companies were then analyzed, compiling a list of trends and best practices.

3.1. Lack of Common Green Terminology, Metrics, Data, and Policy

While it is commonly accepted that the effects of climate change need to be addressed to protect both human and environmental health, it is not widely understood what steps need to be taken to accomplish this daunting task. Inconsistencies across the U.S. government and industry sustainability plans and policies showcase the confusion and misunderstanding within the "green" space, a term that has been broadly used to capture practices that seek to benefit the environment [18].

Both public and private organizations are leveraging exploding prevalence of the term "green" and the confusion that ensues as an opportunity. Organizations are rushing to adopt green practices despite the lack of formal definition of what constitutes a "green" company or "green" best practices. Individual government agencies are implementing various sustainability-focused practices but often have different documented sustainability goals and policies compared to one another. Few federal-level policies exist, and, if they exist at all, most are suggested goals rather than defined guidelines for implementations or timelines for adoption. Sustainability practices in the private sector are similarly unclear and vary drastically in defined priorities and adopted practices. Certifications and posted ratings of "green" companies further complicate the perception of the term.

One widely recognized "green" certification is the Leadership in Energy and Environmental Design (LEED) certification [24], although industry leaders also adopt other newer certifications. Google, for example, is using the Living Building Challenge (LBC) Materials Petal certification for its facilities, which would certify that every building product on site has been vetted against the LBC's Red List of worst-in-class chemicals that pose human and environmental health concerns [25]. Apple has used the Building Research Establishment Environmental Assessment Method (BREEAM) certifications [26]. For companies or organizations that choose to pursue sustainability efforts, there are several more Green Building Certifications available. As compiled in [27], the top 11 certificates are:

- Government-stipulated
  - Energy Star.
  - National Australian Built Environment Rating System (NABERS).
- Private Sector-led
  - Leadership in Energy and Environmental Design (LEED).
  - International Living Future Institute's Living Building Challenge (LBC).
  - Building Research Establishment Environmental Assessment (BREEAM).
  - WELL Building Standard.
  - GreenGuard.
  - Green Star.
- Public–private partnership
  - National Green Building Standard (NGBS).

– Green Building Initiate (GBI) and American National Standards Institute's (ANSI) GREEN Globes.
– International Code Council's International Green Construction Code (IgCC).
– Comprehensive Assessment System for Built Environment Efficiency (CASBEE).
– ANSI/ASHRAE/USGBC/IES Standard 189.1-2014: Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings (ASHRAE 189.1).

Over the last few decades, the U.S. federal government has taken steps toward implementing sustainability policy, though these changes have been minimal and more aggressive policy is needed to make substantial impact. In particular, few major laws regarding sustainability have been passed since the mid-2000s. The Energy Policy Act of 2005 [28] introduced tax incentives and loan guarantees for various energy sources, while the Energy Independence and Security Act of 2007 [29] aimed to move the U.S. toward greater energy independence and security through the increase of clean renewable fuels. For over a decade, only sustainability plans and guidelines had been released.

In 2015, a comprehensive document, Planning for Federal Sustainability in the Next Decade [30], was placed into effect, outlining the federal government's 10-year plan for implementing more sustainable practices. Following this, several other guidelines were released, including Executive Order 13834 (Efficient Federal Operations) [31] in 2018 and the Guiding Principles for Sustainable Federal Buildings and Associated Instructions [32] in 2020. EO 13834 "affirms that it is the policy of the United States that agencies meet energy and environmental performance statutory requirements in a manner that increases efficiency, optimizes performance, eliminates unnecessary use of resources, and protects the environment" and that "agencies are tasked to prioritize actions that reduce waste, cut costs, enhance the resilience of federal infrastructure and operations, and enable more effective accomplishment of its mission". Additionally, EO 13834 was revoked by EO 13990, Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis, which "directs all executive departments and agencies to immediately review and, as appropriate and consistent with applicable law, take action to address the promulgation of federal regulations and other actions during the last 4 years that conflict with these important national objectives, and to immediately commence work to confront the climate crisis" and revokes many EOs from the prior administration [33]. While these documents encourage more sustainable practices, they do not contain quantifiable goals or metrics in order to drive impactful, widespread change across the U.S. government and, by extension, the nation.

The tumultuous nature of undoing and reimplementing sustainable initiatives further complicates the U.S. government's stance on sustainable practices. The U.S. officially withdrew from the Paris Climate Agreement in 2020. In addition, several climate-focused initiatives were canceled in the late 2010s, such as the Navy's Climate Task Force which was shut down in 2019 [34]. Beginning in 2021, however, drastic changes were made across the government that showcased a heightened commitment to sustainability. Not only did the U.S. re-enter the Paris Climate Agreement [35], but many climate change-focused EOs were put into place, such as EO 13990 (Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis [33]), EO 14008 (Tackling the Climate Crisis at Home and Abroad [36]), and EO 14013 (Rebuilding and Enhancing Programs to Resettle Refugees and Planning for the Impact of Climate Change on Migration [37]).

These orders not only established various environmental policies but made a strong statement about the government's stance on the environment moving forward. Over the next few years, the government is expected to make further legislation regarding climate change, environmental protection, and sustainability. As discussed in the next section, the governance of their implementation will require common terminology and metrics that allow to trace not only compliance with such regulations, but also their effectiveness over the following years.

3.2. Observations on Barriers to Green Best Practices

Some of the barriers to green best practices lie in the realm of diplomatic, information, economic, politics, social, and law enforcement. To date, most of the standards and certifications that accompany green best practices are voluntary. Given the widespread recognition of the effects of climate change, it is time to begin codifying these best practices and instituting policy, regulations, and legislation. The barriers to implementing these practices need to be addressed on a nationwide scale. For example, it is difficult to integrate equipment from various vendors to establish a smart building; large buildings may require different standards than smaller buildings. Furthermore, terms such as "green", "net zero", and "LEED" are interpreted in different ways, depending on the user, highlighting the need for clearly defined terms, metrics, and standards. In the U.S., regulatory codes such as land use and building codes are state rights, but even these codes can vary from county to county. Only two states within the U.S. have statewide codes.

With the introduction of such standards and codes, acquisition standards can now include requirements for information technology (IT) electronics used within the buildings to be Electronic Product Environmental Assessment Tool (EPEAT) registered. As EPEAT requirements additionally meet ENERGY STAR requirements [38], devices meeting these standards also qualify as reducing environmental and energy impacts during operations and maintenance.

A full examination of the barriers to green best practices is needed in order to determine the level of difficulty and the cost in some cases of overcoming those barriers. In the meantime, making use of simulation and machine learning to have a better understanding of these practices, where to feasibly set standards, and to learn what the anticipated second- and third-order effects are with the system of systems can also provide a way to overcome the barriers.

3.3. Recommendations for Green Metrics Developments and an Example

In the last section, we identified and presented several certifications successfully applied in practice, and many of them address sustainability planning, such as house metrics and codes. Our proposed way forward is to use the same metrics associated with these certifications in real systems as well as in digital representations.

Given its widespread use across both industry and government, the U.S. Green Building Council's LEED certification was chosen as our example case. The metrics outlined for this certification can also be used for computational decision support, as discussed throughout the remainder of this paper.

The LEED score card [24] contains nine categories with various subcategories. In practice, a project can self-evaluate and submit its description for certification. For this investigation, the metrics defined through LEED will be translated to metrics for the digital twin simulation. Figure 4 shows the current score card with its categories and subcategories. Details of the score card are as follows.

The Location and Transportation category encapsulates the site location considerations (finding a site near or already with existing infrastructure) and methods of access for transportation (ways to reward alternatives to conventionally fueled automobiles). This category rewards points for the following: Sensitive Land Protection, which aims to reduce the environmental impact from the location of a building on a site; High Priority Site and Equitable Development, which aims to encourage project location in areas with development constraints and promote the ecological, cultural, and community health of the surrounding area; Surrounding Density and Diverse Uses, which aims to conserve land and protect farmland and wildlife habitat by encouraging development in areas with existing infrastructure; Access to Quality Transit, which aims to explicitly encourage development in locations shown to have multimodal transportation choices; Bicycle Facilities, which aims to promote bicycling and transportation efficiency and reduce vehicle distance traveled; Reduced Parking Footprint, which aims to minimize the environmental harms associated with parking facilities, including automobile dependence, land consumption, and rainwater runoff; and Electric Vehicles, which aims to reduce pollution by promoting alternatives to conventionally fueled automobiles.

LEED v4.1 BD+C: Core and Shell
Project Checklist

Project Name:
Date:

Y	?	N			
			Credit	Integrative Process	1
0	**0**	**0**	**Location and Transportation**		**20**
			Credit	LEED for Neighborhood Development Location	20
			Credit	Sensitive Land Protection	2
			Credit	High Priority Site and Equitable Development	3
			Credit	Surrounding Density and Diverse Uses	6
			Credit	Access to Quality Transit	6
			Credit	Bicycle Facilities	1
			Credit	Reduced Parking Footprint	1
			Credit	Electric Vehicles	1
0	**0**	**0**	**Sustainable Sites**		**11**
Y			Prereq	Construction Activity Pollution Prevention	Required
			Credit	Site Assessment	1
			Credit	Protect or Restore Habitat	2
			Credit	Open Space	1
			Credit	Rainwater Management	3
			Credit	Heat Island Reduction	2
			Credit	Light Pollution Reduction	1
			Credit	Tenant Design and Construction Guidelines	1
0	**0**	**0**	**Water Efficiency**		**11**
Y			Prereq	Outdoor Water Use Reduction	Required
Y			Prereq	Indoor Water Use Reduction	Required
Y			Prereq	Building-Level Water Metering	Required
			Credit	Outdoor Water Use Reduction	3
			Credit	Indoor Water Use Reduction	4
			Credit	Optimize Process Water Use	3
			Credit	Water Metering	1
0	**0**	**0**	**Energy and Atmosphere**		**33**
Y			Prereq	Fundamental Commissioning and Verification	Required
Y			Prereq	Minimum Energy Performance	Required
Y			Prereq	Building-Level Energy Metering	Required
Y			Prereq	Fundamental Refrigerant Management	Required
			Credit	Enhanced Commissioning	6
			Credit	Optimize Energy Performance	18
			Credit	Advanced Energy Metering	1
			Credit	Grid Harmonization	2
			Credit	Renewable Energy	5
			Credit	Enhanced Refrigerant Management	1
0	**0**	**0**	**Materials and Resources**		**14**
Y			Prereq	Storage and Collection of Recyclables	Required
			Credit	Building Life-Cycle Impact Reduction	6
			Credit	Environmental Product Declarations	2
			Credit	Sourcing of Raw Materials	2
			Credit	Material Ingredients	2
			Credit	Construction and Demolition Waste Management	2
0	**0**	**0**	**Indoor Environmental Quality**		**10**
Y			Prereq	Minimum Indoor Air Quality Performance	Required
Y			Prereq	Environmental Tobacco Smoke Control	Required
			Credit	Enhanced Indoor Air Quality Strategies	2
			Credit	Low-Emitting Materials	3
			Credit	Construction Indoor Air Quality Management Plan	1
			Credit	Daylight	3
			Credit	Quality Views	1
0	**0**	**0**	**Innovation**		**6**
			Credit	Innovation	5
			Credit	LEED Accredited Professional	1
0	**0**	**0**	**Regional Priority**		**4**
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
0	**0**	**0**	**TOTALS**	Possible Points:	**110**

Certified: 40 to 49 points, **Silver:** 50 to 59 points, **Gold:** 60 to 79 points, **Platinum:** 80 to 110

Figure 4. LEED score card, version 4.1 [24].

The Sustainable Sites category encapsulates the choices made to cohabitate with the existing ecosystem at the chosen building site. This category rewards points for the following: Site Assessment, which aims to assess site conditions, environmental justice concerns, and cultural and social factors, before design; Protect or Restore Habitat, which aims to conserve existing natural areas and restore damaged areas; Open Space, which aims to create exterior open spaces; Rainwater Management, which aims to reduce runoff volume; Heat Island Reduction, which aims to minimize heat islands; and Light Pollution Reduction, which aims to increase night sky access and improve nighttime visibility.

The Water Efficiency category encapsulates various efforts to reduce water consumption. This category rewards points for the following: Outdoor Water Use Reduction and Indoor Water Use Reduction, which aim to reduce potable water consumption and preserve no- and low-cost potable water resources; Optimize Process Water Use, which aims to conserve low-cost potable water resources used for mechanical processes while controlling corrosion and scale in the condenser water system; and Water Metering, which aims to conserve low-cost, potable water resources and support water management and identify opportunities for additional water savings by tracking water consumption.

The Energy and Atmosphere category encapsulates reducing energy usage and transitioning to renewable energy sources. This category rewards points for the following: Enhanced Commissioning, which aims to further support the design, construction, and eventual operation of a project that meets the owner's project requirements for energy, water, indoor environmental quality, and durability; Optimize Energy Performance, which aims to achieve increasing levels of energy performance beyond the prerequisite standard; Advanced Energy Metering, which aims to support energy management and identify opportunities for additional energy savings by tracking building-level and system-level energy use; Grid Harmonization, which aims to increase participation in demand response technologies and programs; Renewable Energy, which aims to increase the supply of renewable energy projects; and Enhanced Refrigerant Management, which aims to eliminate ozone depletion and global warming potential and support early compliance with the Montreal Protocol, including the Kigali Amendment.

The Materials and Resources category encapsulates efforts to choose products and/or raw materials that have been sourced responsibly and that minimize the use and generation of harmful substances. This category rewards points for the following: Building Life-Cycle Impact Reduction, which aims to encourage adaptive reuse and optimize the environmental performance of products and materials; Environmental Product Declarations, Sourcing of Raw Materials, and Material Ingredients, which aim to encourage the use of products and materials for which life-cycle information is available and that have environmentally, economically, and socially preferable life-cycle impacts; and Construction and Demolition Waste Management, which aims to reduce construction and demolition waste disposed of in landfills and incineration facilities.

The Indoor Environmental Quality category encapsulates efforts to improve air quality throughout construction and occupancy of the building. This category rewards points for the following: Enhanced Indoor Air Quality Strategies, which aims to improve indoor air quality; Low-Emitting Materials, which aims to reduce concentrations of chemical contaminants that can damage air quality and the environment; Construction Indoor Air Quality Management Plan, which aims to minimize indoor air quality problems associated with construction and renovation; Indoor Air Quality Assessment, which aims to establish better quality indoor air in the building after construction and during occupancy; Thermal Comfort, which aims to provide quality thermal comfort; Interior Lighting, which aims to provide high-quality lighting; Daylight, which aims to introduce daylight into the space; Quality Views, which aims to provide a connection to the natural outdoor environment by providing at least some unobstructed views; and Acoustic Performance, which aims to promote effective acoustic design.

The remaining categories encapsulate higher-level system design. The Integrative Process credits aim to support high-performance, cost-effective, equitable project outcomes through an early analysis of the interrelationships among systems; the Innovation credits aim to "encourage projects to achieve exceptional or innovative performance to benefit human and environmental health and equity" and to "foster LEED expertise throughout building design, construction, and operation and collaboration toward project priorities"; and the Regional Priority credits aim to provide an incentive for the achievement of credits that address geographically specific environmental, social equity, and public health priorities.

As discussed above, LEED provides a variety of metrics that can be utilized for a digital twin model. One benefit of LEED as the driving sustainability guideline is that these different metrics can be leveraged for various applications and priorities, creating a customized approach. It is noteworthy that there is a synergy with the building information modeling (BIM), as this method allows code assessment and evaluates progress against provided metrics [39]. Using LEED-defined metrics within BIM therefore seems a viable approach, as also suggested in [40].

An example of a related effort is project SPHERE supported by the European Union as part of their Horizon 2020 efforts. SPHERE aims to provide a BIM-based digital twin platform to optimize the building life-cycle, reduce costs, and improve energy efficiency in residential buildings [41]. Although focused on buildings, their research shows the applicability of real-world standards to the development of digital twins to support sustainability for the physical twin, as discussed in [5] as well.

In the reminder of this paper, we focus mainly on the already-matured technologies supporting digital twin development for the technical components of a city modeled as a sociotechnical system. However, we will address the social components in the discussion, as it is pivotal to understand the current maze of socially implied metrics that influence the technical aspects as well.

4. Digital Twin Technology for Sustainability Planning

We propose to combine the way that real-life sustainability contributions are measured and certified with the power of digital twins of buildings for planning, as well as monitoring their performance, with regards to being sustainable.

4.1. Digital Twins and Sustainability Planning

Digital twins already have a history in sustainability planning, although the main focus has been on a smaller scale, particularly for buildings [39]. Building codes and guidelines for data centers are one example where digital twins positively contribute to sustainability planning, such as how to reduce the power consumption, reduce heat emission, etc. Our recent literature survey [19] shows that comparable studies have been performed for buildings, smart cities, etc. A digital representation of the city and its buildings—planned or actual—can enable planners to make decisions that lead to sustainable solutions. Digital twins can help plan efficient use and design, identify infrastructure requirements and enhancements, and optimize operational planning and execution. As a result, resources can be conserved, systems can be monitored and made more efficient, and processes can be modeled to make use of predicting and forecasting.

Nochta et al. [42] envisioned the use of an extension of digital twins to an urban analytic tool. The city-scale digital twin (CDT) takes social–political and technical aspects into account. CDT is for decision-making in "urban planning, management and associated services" at the city level. When utilizing CDT, three issues need to be addressed. First, defining what is meant by a "realistic digital representation". Second, deciding what "city-level decision-making processes" will be explored in CDT. Lastly, prior to jumping into CDT modeling, a thorough investigation of the "status quo" should be completed so that expectations can be set as to what improved insights are needed. However, at the time of writing this paper, CDTs are conceptual ideas that are not yet implemented for practical applications.

4.2. Planning Efficient Use and Design

Digital twins support feasibility evaluation during the requirements analysis and initiation phase, allowing accomplishment of trade-off analyses and experiments without the need to have the real system already present. For the buildings of interest, the digital twins of these buildings expose the same attributes that are of interest for the real system as well. Using BIM methods, as described in [43], these parameters can be unambiguously defined and specified. Using these specifications then allows one to define digital twins as desired to evaluate the intended behavior [39,41]. In addition, the broader applicability of systems engineering artifacts to help to define digital twins is described in detail in [44].

In support of sustainability planning, the 57 metrics identified in the LEED score card are obvious candidates. While most of them are static, some address the dynamics of the building as well, such as energy consumption, contribution to the heat index, etc. This allows a first well-educated guess regarding the sustainability of the individual buildings. How the buildings are composed into a city and what these mean for the supporting infrastructure is addressed in the next section.

4.3. Identification of Infrastructure Requirements and Enhancements

In the development phase, digital twins are used in support of specifications, helping to reduce ambiguities. This is true for individual building and object contributions to the urban development. Even more importantly, in this step, the buildings and supporting infrastructure objects are composed of the city components of interest, while keeping in mind infrastructure requirements and enhancements [45]. By placing the digital twins into a situated, synthetic, common environment, the interplay of these smart buildings within the city component can be simulated. As discussed in [46], this also allows the methods of artificial intelligence and machine learning to support heuristic optimization. It also allows the simulation of the city as a complex structure.

The situated, synthetic, common environment allows for extensive experiments with building layout before selecting the most desirable one. It allows the placement of smart devices and buildings under the realistically represented constraints of the target area. Smart devices support weather sensing, public safety, waste management, leak detection in utilities, smart parking, water quality, structural integrity of buildings or bridges, soil conditions, public health, water levels of sewage and drain runoffs, air quality, safe and orderly streets, smart lightning, and more. It should be noted that the simulation is reflecting the concepts depicted in Figure 2. Digital twins can be smart and metered infrastructure with devices supporting smart rooms and smart buildings. As such, this reflects the multiple layers as well as the interconnections. As the simulation created by embedding the digital twins into the synthetic environment allows numerical insights into the dynamic behavior of the resulting system of systems, it also allows for the discovery and governance of the emergent behavior of this complex, adaptive system created by the collection of smart devices and smart buildings into a smart city. Achieving this will lead to an increase in sustainable solutions, as envisioned for the general case in [47]. This simulation is not only a computational decision support tool for development, it also has its place in operations and maintenance.

It should be noted that this approach can include existing buildings as well, as discussed in [48]. However, in cases where digital twins are created for existing buildings for the sole purpose of representation of systems in the synthetic world, the feedback from physical to digital twin and vice versa is often inferior to the cases in which an integrated approach was chosen from the beginning.

4.4. Optimizing Operational Planning and Execution

Finally, in the operations and maintenance phase, the physical system is connected to its digital twin through sensors. The digital twin is continuously calibrated with information from the real system, in real time, as well as with data-analytic results.

In particular, when using a mature simulation approach, as described in [6], in which each device and building is represented by a digital twin in the form of an intelligent software agent, there are opportunities to venture far beyond what is prescribed in controls and regulations. Examples are the following.

- As the simulation predicts the usual trajectory through the city system states, anomalies can be detected by comparing predicted and observed behaviors. This allows timely remedial actions in case of a fault, error, or an emergent unfavorable development.
- As discussed in [46], the approach augments data-driven forecasting, as enabled by machine learning approaches and by knowledge-driven prognosis, as the simulation system explicitly represents functional dependencies so that results are easier to explain.
- In the case of malfunctions of buildings or smart devices, the simulation can quickly be used to reconfigure the physical systems. As such, the digital twins can contribute to contingency plans as well as ensuring sustainability in the events of natural or manmade disasters.

- The idea of predictive maintenance is already established in domains such as manufacturing [49]. The concepts can be applied to sustainability in urban developments. Related ideas can be found in [50].
- Merging big data analytics with the concepts of digital twins allows for the calibration of the digital twins with real-world insights as well as applying the same analysis tools to provide insights from the simulation to the planners and decision-makers. This includes massive simulations to better cope with uncertainties and their effects, as well as providing multiple alternative views, based on different prediction models, that help to identify stable solutions.
- In addition to these specific methods, using the approach described here allows one to utilize the full toolset to support the governance of complex systems [1], as envisioned early in our introduction.

In summary, the proposed approach implements the concepts captured as a vision by Filip in [2], namely, a system that enables computational decision support and control for large-scale complex, adaptive systems.

5. A Metrics-Driven Framework for Sustainability Planning

We propose to align the research of several domains towards the creation of a metrics-driven framework to address the challenges in sustainability planning. This paper also serves as a call for action to the communities providing the referenced work to align with it for better computational decision support for sustainability planning.

5.1. A Method for Providing Computational Decision Support

Based on the observations in this work, the need for computational decision support is motivated by the insight that sustainability planning falls into the problem category addressed by complex, adaptive system methods. The buildings and devices can be interpreted as individual actors that can not only react themselves, but can also be reached from the outside, either by sensors, messages, or through external access to building and device controls. In general, these actors act based on their perceptions and may build local, self-organized groups to support mutual objectives, such as optimizing traffic flows to minimize emission of exhaust fumes, or the optimization of rainwater drainage to avoid soil contamination. The resulting interplay of buildings and devices that utilizes a set of rules and adapts their behaviors to optimize the overall result towards their individual goals would result in a complex, adaptive system. Similar observations and recommendations for computational decision support can be found in [51,52].

Establishing the framework is facilitated by the fact that most specifications for buildings are detailed enough to provide at least a blueprint for a digital twin. A recent review of existing applied methods is compiled in [53]. In addition, Deng et al. describe how the BIM can be used to support the development of digital twins [54].

Creating the rules that guide system behavior is a domain-specific endeavor. However, many system changes are governed by the underlying physics, such as air flow or temperature diffusion, and there is a rich body of knowledge that the community can draw from, such as [55] and others. For the domain-specific rules, the identified metrics and control algorithms become pivotal. For sustainability, we showed how the LEED score card could serve as a starting point, although some of the criteria, such as innovation, only affect the technical approach tangentially. Implementing these parameters as variables in a digital twin makes the definition unambiguous and easy to communicate.

Finally, we have to embed all buildings and devices in a common, situated, synthetic environment that allows computing interchanges between buildings and resulting effects. Such effects can be intended or unintended. For example, smaller buildings in the shadows of bigger buildings may require more lighting, but they also potentially have less need for heating, ventilation, and air conditioning (HVAC). As is the case with every simulation, only properties and effects captured in the conceptual model can be taken into account. Choosing the appropriate abstraction level and detail is therefore as important as scoping the system to comprise all relevant properties and concepts. Many new devices are generating less heat when compared to the earlier models, which reduces their power consumption; however, such decrease in heat generation may actually result in the need for additional heating systems in the buildings to cope with cold weather. Similar interdependence can be observed in the city component that the urban planner is interested in as well. Karnama et al. [56] provide examples for redirecting generated heat into other facilities that need it, such as greenhouses, swimming pools, nearby buildings, district heating, and so forth.

We present two use cases that highlight two important aspects of this framework. The first use case focuses on the use of digital twins for forecasting, trade-off analysis, and other sustainability efforts. The second use case deals with the physical twin equipped with sensors that drive the digital twin. While the first use case is based on examples out of the USA, the second use case shows related activities in the European Union to demonstrate the general applicability of the proposed method.

5.2. Use Case One—Sustainable Data Centers

The first use case is derived from the well-documented example of using digital twins to develop a sustainable data center [57], where many aspects can be directly transferred into recommendations for sustainable commercial buildings. With the rise of data centers in the early 2000s, it was found that data centers were huge consumers of electricity, and it was thought that computing would not be sustainable given the demand growth indicators then [58]. Much research was since carried out, and solutions to make data centers more energy-efficient were placed into practice [59]. In 2020, Masanet et al. found that energy efficiency trends between 2010 and 2018 help to counteract the growth indicators of global data center energy demand. However, this study estimated that demand growth indicators will start to overcome current efficiencies by the 2023/2024 timeframe [59].

One of the key research findings in our literature survey was in the application of data center digital twins to experiment with and uncover where efficiencies in computing can be gained [19]. The use of digital twins applied to data centers has benefits in the following areas:

- Planning and implementation: Building of new data centers or upgrading existing ones allows for the examination of the effects on sustainability throughout the planning process.
- Operations and maintenance: Monitoring a data center 24/7 allows inefficiencies to be discovered and ensures that the data center continues to fall within its performance criteria throughout day-to-day operations.
- Expansion and evolution: New sustainable practices implemented in the digital twin allow for the examination of the new practices to ensure the system behaves as expected, and help to uncover potential second- and third-order effects.

In the planning and implementation phase, choosing to achieve an LEED certification as the sustainability standard allows the use of parameters and metrics that reside within that standard. Adopting the standard first gives us the quantifiable goals that we desire to achieve. Reddy et al. [57] laid out the taxonomy for data center metrics and suggested metrics for each category in the taxonomy. In their paper, they presented nine category dimensions with applicable absolute and relative metrics. The nine categories, their definitions, and known issues are described in Table 1. While the categories "network" and "storage" are specific to data centers, the other categories can be generalized to cope with sustainability.

Table 1. The nine metric categories identified in [57].

Dimension	Use	Issues
Energy Efficiency	These metrics are a series of indicators relevant to the quantitative measure of energy efficiency of a data center and its components. Some metrics are used to know how efficiently a data center transfers power from the source to the IT equipment, and some metrics define IT load versus overhead.	Energy consumption data disaggregated by data center subcomponents may not be available. It is hard to know the number of operating systems and virtual machines running in a data center.
Cooling	These metrics characterize the efficiency of the HVAC systems and how well these serve the cooling demand.	It is challenging to determine whether there is adequate underfloor cooling in a consistently advancing environment, where heat densities change within each of the racks as well as from one rack to the next. Data center cooling systems must balance ambient environment with supplemental cooling to optimize efficiency.
Greenness	These metrics explain the carbon footprint of the data centers and IT equipment. Additionally, we can assess how much green energy is used, how much energy is exported for reuse, and how efficiently a data center is using water.	Some of these metrics require seasonal benchmarking to capture region and season changes.
Performance	These metrics measure the productivity of a data center, effectiveness in delivering service, and agility in responding dynamically to change.	”Useful computing work” is not defined uniquely. Correct base scores may be challenging without the right tools.
Thermal and Air Management	These metrics help us to take care of efficient air flow, temperature issues, and aisle pressure management.	It is difficult to make proper aisle arrangement. For efficient airflow, we must address bypass and recirculation of air flow.
Network	These metrics give the data center network energy efficiency, utilization, and traffic demands.	Measuring variable energy varies from one operator to another. Useful work is not defined properly.
Storage	Using these metrics, storage operations and performance can be monitored. We obtain better visibility into how proficiently our capacity is being utilized to store client information.	Measuring customer stored data and their criticality is difficult due to data duplication, and the user’s view differs from the storage frame view.
Security	These metrics are useful for protecting servers from attacks and they continuously monitor physical and virtual servers and clouds. Further, these metrics cover some basic measurements of firewall performance in a data center.	These metrics are highly dependent on internal governance and compliance standards.
Financial Impact	These metrics calculate total cost of ownership, financial impact of data center outages, return on investments on management tools, and technologies for sustainable data centers.	Confidentiality concerns associated with revealing costs for a particular facility. Carbon credit may vary based on the country’s policies.

Given the objectives to minimize and maximize metrics and to compute optimal conditions, Reddy et al. stopped short of setting a standard for the metrics identified, and relied on improvements over the current conditions [57]. This should be brought to the attention of the governance of the sustainability standard, such as LEED, so that further research can be carried out towards establishing a robust standard of metrics.

Second, while monitoring the data center during the operations and maintenance phase, the chosen sustainability standard will continue to be used as the requirements driving the performance criteria in day-to-day operations. When testing new components or varying workloads within the data center digital twin, the monitoring process will allow the operator to determine if the new components or workloads allow the data center to operate within the chosen sustainability standard. Data center business management software, such as Data Center Infrastructure Management Software (DCIM) [60], helps to automate the monitoring of both information technology and the capacity planning processes. A company called Future Facilities has already built a data center twin application to predict facility operations under varying conditions in order to optimize "business goals with facility operations and efficiencies" [61].

Last, the expansion and evolution phase allows for the examination of all sustainability standards to ensure that any changes to the data center system of systems will not inadvertently cause a related metric or an unknown related metric within the environment to violate the sustainability standard as a result of a second- or third-order effect. Results presented in [62] discuss how to optimize when hardware refresh should occur, and simple and affordable techniques are summed up in [63]. Taylor discusses ways to optimize all other physical aspects of a data center, such as operating costs, electrical power consumption, cooling, floor space usage, information technology through instrumentation, and software [60]. Nochta et al. [42] highlight the need for sociotechnical exploration within city digital twins to fully understand the impact of the environment, as discussed in previous sections and will be discussed further in the following section.

The use of digital twin technology can aid in a variety of functions within a data center [61]. "Temperature or energy aware scheduling, dynamic voltage frequency scaling, resource virtualization, improving algorithms used by applications, switching to low-power states, power capping, and shutting down unused servers can also contribute to data center efficiency" [64]. Additionally, the use of business management software, coupled with simulation and machine learning, can help explore and optimize data center algorithms for modeling and predicting power consumption and performance, as well as manage workload consolidation.

This use case focuses on the use of digital twins in the various phases of the life-cycle of buildings, using several studies and their reported research results to make the case that it is possible to support all phases with digital twin technology.

5.3. Use Case Two—Enhancing Sustainability on a University Campus Complex

In our second use case, we present an example that represents a first step towards a full-fledged use of digital twins in efficient, green-oriented building planning and management described by Mavrokapnidis et al. [65]. The Technical University of Crete (TUC) in Greece has developed a building management system of low-cost Internet of Things (IoT) sensors, which are installed in a number of buildings on the TUC campus to augment the building energy management system (BEMS) currently in place. Deployment of the sensors, called OpenLink, was carried out in three stages in 2015, 2018, and 2020 (Figure 5).

Over 6000 sensors are installed in over 300 rooms across 16 student residence halls on the TUC campus. The sensors are configured and managed via Web interface, continuously monitor the energy usage in the rooms, taking into consideration the room occupancy, and proactively collect energy consumption data for analysis by the system application program. The goal is to increase campus sustainability by reducing operation costs through identifying usage inefficiencies and detecting energy-consumption abnormality.

Figure 5. The grouping of buildings equipped with sensors on the Technical University of Crete campus (photo courtesy of Georgios N. Lilis and Kyriakos Katsigarakis).

Mavrokapnidis et al. [65] applied the apparatus of the TUC building management system as their use case in their research. They proposed a methodology of fusing static and dynamic building data from different sources, and tested this methodology by utilizing the data gathered from these OpenLink sensors. The high-level system architecture of the TUC building management system is shown in Figure 6.

In their use case, the OpenLink sensors from different rooms of a physical building wirelessly transmit data to their respective remote terminal units (RTUs). The RTUs then forward the collected data to the system middleware via the Modbus TCP/IP. The middleware parses the received data and stores them in a database (e.g., PostgreSQL, MySQL, InfluxDB, etc.). The building management system is centrally managed through a Web-based server. The server uses digital twins of the campus buildings to interpret the data. Using the information from the digital twin as well as the data received from the physical twin sensor, the front-end application produces graphical output of desired information such as building topology, electrical equipment, energy meters, and HVAC. The displayed information can then be utilized for advanced analytics and computation of optimal control.

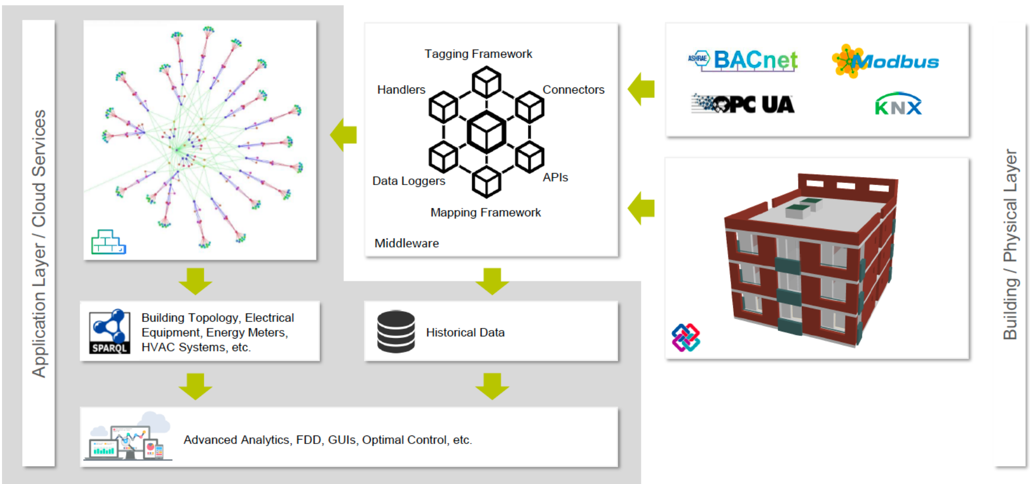

Figure 6. The high-level architecture of the IoT-enabled building management system.

To realize a network of IoT sensors at scale, the devices need to be inexpensive to acquire and maintain. For this research effort, the hardware and software infrastructure to support the sensing devices was developed by OpenLink. Each sensor costs EUR 30 for the hardware, installation, and configuration. Typical commercial solutions (e.g., KNX sensors) would each cost EUR 650 for comparable deployment.

The installation of IoT sensors in the TUC campus buildings is a first step towards building a digital twin model to study the green best practices of building design and management. The digital twin model can be constructed using BIM, which is a collection of static data, and the live information from the IoT sensors representing the dynamic data. While the first phase focused on developing the digital twins, the second phase provides the proof of feasibility for feeding the digital twins with data of the physical twins, and shows that with proper planning this can be achieved in cost-efficient and sustainability-enhancing ways.

It should be noted that this infrastructure was built initially to monitor these TUC building premises and to apply control strategies developed for the European Union project Building as a Service (BaaS) [66,67]. The same infrastructure will also be used to calibrate the building energy performance simulation models (BEPS) of the buildings, which are generated automatically from the respective building information models (BIMs) using the tools of a Web platform [68]. To realize this automatic generation, this platform implements the algorithms described in [69,70]. The calibrated BEPS model, together with the existing building semantic graph, can form a building digital twin that can surrogate its physical counterpart and predict the building's energy performance behavior.

5.4. Future Developments

The proposed approach to develop digital twins and embed them into a commonly situated, synthetic environment allows one to compute all the interactions and dynamics of interest to the sustainability planner and has a lot of potential for additional developments.

First, this approach allows one to visualize the whole project by using immersive technology provided over the full range of virtual reality (VR). Using VR methods, planners can experience the city component of interest in early phases They can also utilize augmented reality (AR) to project planned buildings into the real environment to receive an even more realistic impression. Several examples for the use of such immersive environments for sustainability planning are given in [71]. For sustainability, it may be useful to also display data or visualize effects of interests, such as heat surfaces of buildings that change with different colors or isolation materials, or the amount of daylight usable in a room depending on the surrounding buildings and the resulting shadows.

Second, the synthetic environment can reflect the different climate conditions to check the efficiency of regulations and their metrics for a given region or a given season. Some measures will work well in the summer but may contribute nothing in the winter. Sustainability efforts that work very well in Boston, Massachusetts, may have no effect in Madrid, Spain. Regulations contributing to breakthroughs in Berlin, Germany, may have very little effect in San Diego, California. Simulation of various regional and seasonal climate conditions will help to better understand the applicability and usefulness of the common green metrics described in the first part of this paper.

Third, the synthetic environment can be calibrated to reflect possible climate change effects. Using standard interfaces allows one to import not only environmental data, such as the Environmental Dataset Gateway (EDG) [72], but also future data on environmental conditions, e.g., from climate forecast models. This allows for the computation of possible effects of climate change on sustainability, such as those documented in [73]. This needs to include methods for urban heat island effect prediction to address the needs and concerns for citizens before it is too late.

Finally, the synthetic environment populated with the digital twins of buildings and devices of interest can be augmented by socially capable software agents, representing human individuals and their social interactions. In other words, we create an artificial society that can evaluate the human, social, and cultural aspects, as discussed in [74], of the sociotechnical complex system that the urban planner has to design and govern. An example for such an artificial society to compute the social interactions between agents constrained by policy, as well as physical constraints of their environment, is documented in [75], where hundreds of thousands of agents are populating Chicago, Illinois, and its suburbs. This allows one to not only better understand the effect of policies and regulations, but also to help better understand long-term effects on the social structures, as envisioned in [76]. After all, the urban planners focus on sustainability, but the design of the city component is focused on the humans who will live in the city, including aspects documented as challenging topics in [42]. As artificial societies can take the social determinants of the environment into effect as much as the diversity background of the individuals, the ultimate extension allows one to address challenges of equity as well, such as ensuring that underserved communities are not unfairly affected by sustainability or other policy decisions. The first ideas to extend the metrics to make them applicable in these wider contexts are presented in [77].

6. Conclusions

In this paper, we started with observing real-world efforts to increase sustainability and provided certificates for efforts that strive to achieve this goal. The certificates use scorecards that can be used as metrics to measure the success not only for real efforts, but also for digital representations. We observed that several of these real-world metrics need to be specified in more detail and agreed upon on a broader scale to not only support regulators and policymakers but also the developers of computational support tools for the planning of systems targeting to fulfill these metrics, including digital twins.

We presented various examples and pointed to literature describing how to develop and apply digital twins in support of sustainability. Digital engineering practices not only allow to define implementation artifacts for the physical systems, but they are also rich enough to support the generation of digital twins. This allows one to create digital representations of the buildings and devices that are of interest to the sustainability planner, including the processes and their efficiency regarding supporting sustainability as captured by the chosen metrics.

Furthermore, populating a common, situated synthetic environment with these digital twins results in a computational decision support tool for the urban planner with a focus on sustainability, which can even be enhanced if an artificial society is used to populate the resulting model of the new, sustainable city component; however, the use of artificial societies for the computational support of complex decisions under uncertainty for policymakers is still in its beginnings.

Our extensive review of recent research on green metrics and digital twins applied to sustainability challenges shows that many of these technologies and methods already exist, but they are often at home in "stove-piped" research environments, implemented to address certain research questions and not necessarily designed with being reused in a broader context in mind. This paper is a call for action to align these efforts towards the development of the common framework described above, enabling the collaboration of experts from the various disciplines supporting the planning of sustainability in a complex, adaptive sociotechnical system as it is represented by a city component using smart technologies.

7. Discussion

Marcucci et al. started the discussion on policy support based on digital twins [78]. Gilbert et al. argue in [79] that *"where the costs or risks associated with a policy change are high, and the context is complex, it is not only common sense to carry out policy modelling, but it would be unethical not to'.'* We argue that supporting planners in finding sustainable solutions that do not place unnecessary burden on the affected individuals falls into this category.

Besides our compilation of metrics and applicable research, providing the framework to bring these ideas together is a major contribution of this article. A framework is more than the sum of its components. From the engineering viewpoint, a framework provides a broader set of formerly disparate functions as new functionality to a user, supporting all phases of sustainability planning, as discussed in this paper. From the scientific perspective, the solution sets provided by the framework allow for new epistemological insight. As such, we are optimistic that the research presented in this article will contribute to the development of mission-oriented, standardizable solutions, as described in [80], driving innovative procurement to improve the sustainability performance of municipalities beyond voluntary activities, such as recently compiled in [81,82].

Utilizing the new developments in information technology and communications, e.g., advances in 6G, such as described in [83], the framework will allow us to increasingly bring the identified methods together to provide a common methodology. It will allow us to evaluate the efficiency of metrics regarding their contributions to making smart cities not only more sustainable, but also worth living in. We understand this paper not only as a theoretic proof of feasibility and applicability with first practical application examples, but also as a call to action for the communities of sustainability, digital twins, and simulation to collaborate in order to provide the necessary computational decision support tools to our society.

Author Contributions: Conceptualization, A.T.; methodology, all; metrics, C.R.C. and E.G.H.; literature review, C.R.C., S.M.D. and E.Y.H.; use cases, S.M.D. and E.Y.H.; writing—original draft preparation, all; writing—review and editing, all; supervision, A.T.; project administration, E.Y.H. and A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to recognize the support received from the MITRE independent research and development program. They would also like to thank their many colleagues that helped in the underlying research for this paper, in particular Nichole K. Davis, Christine E. Harvey, Jenn Richkus, Sanith Wijesinghe, and Kris Rosfjord from the MITRE Corporation. Furthermore, they are thankful for the discussions with Georgios N. Lilis and Kyriakos Katsigarakis from the University College of London, and Björn Johansson from Chalmers University of Technology in Gothenburg.

Conflicts of Interest: The authors declare no conflict of interest. The views, opinions, and/or findings contained in this paper are those of The MITRE Corporation and should not be construed as an official government position, policy, or decision, unless designated by other documentation. This paper has been approved for public release, distribution unlimited, Case No. 22-0379.

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