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Chapter 7: Creating interconnected digital environments that support real-time insights, adaptive learning, and energy optimization through intelligent infrastructure

7.1 Introduction

This chapter is intended to present and discuss issues in the context of the digitalization process of energy-consuming systems, which is advancing at both the utility-customer and facility sub-system levels. The focus of this research includes the area of real-time insights and predictions as they relate to energy management and optimization purposes. These are the key research foci of the project, which concern technology, data, and information.

This research aims to explore and assess some of the opportunities and practical challenges associated with digitalized interconnected environments, especially when multiple such virtual environments are interconnected. The end goal of research challenging these areas should provide energy management, operations, and maintenance with the possibility of leveraging the analysis results associated with an ever-increasing access to contextual data. The environments we discuss use interconnected technology that sits at increasing distances from the physical environment but are ultimately linked to it. Consequently, the insights and recommendations are based not just on commonalities in the connected environments, but also on the fact that interconnected information and data can be exchanged in close to real-time. In turn, this rapid and frequent exchange of data can provide already successful recommendations and predictions. In other words, the interconnected digital environments provide, over and above currently existing approaches, a near real-time approximation to the analyses that identify as possible energy efficiency or optimal set points for facilities and built assets. The main points tackled during the following discussion are presented in a figure. Emphasis is placed on optimizing aspects and challenges. This paves the way for the coming discussion.

7.1.1. Overview of the Topic and Objectives

The generation of data in numerous fields is constantly increasing and calls for solutions to effectively exploit data in real time. In a smart grid, a multitude of real-time data is available and could contribute to energy optimization, such as distribution system infrastructure data, building status, or even occupant behavior. However, effective exploitation of this data for energy purposes requires a comprehensive overview of available and engaged digital environments. This includes related interconnected domains and their primary functions as they may be directly or indirectly affected by what happens in one of these environments. This essay is intended to introduce those opportunities and to provide insights into what those integrated domains are, understand their main objectives, and determine whether and how energy fits into the overall objectives. In doing so, the report will also identify the main public and private stakeholders leading the initiatives in the different digital environments.

The study therefore aims at addressing the following interconnected objectives: • Introduction of the topic and its goal: an interconnected digital environment to exploit various sources of real-time data for energy management through real-time insights – why is this considered important and what is the gain provided by integrating real-time data coming from different sources? • Presentation of main interconnected digital environments: what they are, what their main objective is, and what sources of real-time data they are exploiting. • Analysis of the availability of the real-time data and their integration in existing digital environments and, in this case, the operational introduction of newly developed frameworks or solutions. This latter aspect is twofold: What is done to engage businesses? What activities, initiatives, policies, and regulations have led to the identification of new real-time integrated platforms?

7.2. The Concept of Interconnected Digital Environments

A digital system functioning in-house, in an industrial plant, in a specific part of a smart city, or across the value chain of a manufacturing company is conceptualized as a digital ecosystem. Equally entwined are those in areas such as smart manufacturing and industrial IoT, location-based services and smart city operation, and energy management in an oil and gas company. Considering real-time operation and decision-making in modern industry, as well as lowering energy consumption across the manufacturing processes, interconnected digital environments that are widely linked can generate relevant insights, lead to efficient responses to technological challenges, and identify successful business models.

In the interconnected digital environment, a set of functions and activities with various computation and intelligence elements and IoT components evolve at different timescales such as sensing, aggregation, real-time control, planning, and performance analysis. Managing complex digital ecosystems underlying interconnected operations, critical process initiatives, performance analysis systems, and business solutions, as well as reaching real-time insights, is a multidisciplinary challenge. In addition to the interrelations among digital machine components and IoT, the complexity of interconnected organizations and the total amount of data exchanged are noteworthy. Lines of communication include interactions between: (1) consumer digital devices, networking, and edge computing; (2) an energy-efficient heterogeneous industrial control system; (3) IT systems; and (4) gateways throughout the company.

One may conceive systems such as the above end-to-end open architecture framework as being assembled from conventional solutions. The solution is assembled together from existing standards and reference architecture. An efficient energy control system would require the help of an interconnected digital solution in an environment that can express conditions, objectives, performances, and constraints across millions of elements in vast interconnected systems. Below we examine the concept of such an interconnected digital environment and its implications.

Fig 7.1: Interconnected Digital Ecosystem - Layers of Intelligence & Control

7.2.1. Understanding Digital Ecosystems and Their Dynamics

Digital business platforms are regarded as digital ecosystems, an interconnected form of platforms on which actors can interact and form relationships (Chakilam, 2022; Challa, 2024; Chava, 2023). Platforms provide opportunities for those willing to collaborate, exchange data, and develop a digital ecosystem. Modern digital ecosystems with more than one stakeholder on a single layer can enhance their capabilities beyond the levels of their individual behind-the-scenes bilateral transactions. For the widest range of transactions, they should be able to support direct system integrations and organizational integration through processes and service delivery networks. Particularly in the context of first-party digital ecosystems, digitalizing data across interdependent organizational boundaries is critical for tackling dynamic conditions between organizations. This includes collaboratively deciding the technical architecture and service delivery model of underlying infrastructures for potential users and data providers to minimize transactional difficulty. The leverage of the collective intelligence that arises from the synergy of the technology architectural choices, data, and end-users' tracks formed in digital ecosystems.

Effective digital ecosystems should have a strategy for acquiring and retaining its network members as they assess what other lateral stakeholders contribute to the digital ecosystems and how their FSP can interact with those stakeholders. They must ensure the satisfaction of all stakeholders, and fidelity must cater to all individuals: customers, the residential population, and accessible data creators. Upstream or sideline game-rule or policy factor considerations were not included here due to the growth opportunities of the ecosystem. The growth of the digital ecosystem can be hindered by adversarial factors. A continuous learning loop is also leveraged from building insights into participants and new data on digital ecosystems towards individuals. The mindset of the ecosystem with real-time, just-in-time analytics remains an important advantage, if not a necessity. This is linked to the evolving dynamics of the digital ecosystem and opts for their methodology over time. The users of digital ecosystems and digital cities change. User requirements are also dynamic in a standard product-market fit-seeking strategy. Regularly updating the landscapes can help the new functions and characteristics that are directed.

7.3. Real-Time Insights: Importance and Applications

In interconnected digital environments, the availability of data can sometimes be immediate. Real-time insights can provide you with timely information and immediate input for your decisions. Real-time insights are valuable for many applications. In energy management, they are crucial, as they allow for the creation of energy optimization strategies. The additional value generated by real-time data can be deployed across various applications for smart cities, energy systems, manufacturing, and for helping the decision-making process in various aspects of our technological world. Immediate interpretation can be translated into distinct valuable tasks, including distribution, reliable energy trades for prosumer communities, energy forecasts, demand management, optimization for generation, storage, and consumption, and emission reductions. The list is long, and the potential is interesting, as real-time data allow for higher operational performance and reduced energy waste. Interesting applications in data-informed platforms have been explored, including smart buildings, smart charging of electric vehicles, management integrated with solar panels and electric vehicles, smart energy storage, and smart meter data analytics for predictive maintenance of energy systems.

Real-time analytics techniques are important in a digitalized world. Companies explore various value services from clusters to distributed players. Significantly, data processing with respect to time is much more critical in some applications. Emerging technologies and methodologies contribute to enriching our insights to provide you with the value you need. Techniques can include real-time big data architectures, stream processing, event-based systems, and edge or fog computing. However, many challenges are still present, including information overload, protocol and data interoperability, latency, and efficiency in data processing. These challenges slow us down in translating data into real value-sourced trends and patterns that we can use to formulate valid real-time decisions.

7.3.1. Data Collection Techniques

Introduction to monitor datasets, a variety of techniques can be used to collect data, out of which some techniques can also be used for energy data. These techniques play an important part in generating real-time insights about operation management. The result of this operation management helps in making adjustments about the workflow, such as choosing the high crop yielding areas, water circulation, machinery status, and building management. There are various sensor and software-based techniques available to collect data. Moreover, for a rich dataset, digitalized surveys can also be used. Utilization of these techniques has made operation cost-efficient and remarkable for making decisions.

In an interconnected digital environment, a number of sensors can be deployed for process measurement and to collect operational data. A product of IoT devices, sensors also help in the management of different grey or scheduling energy resources and capabilities of the entire control system. These interconnected devices can be any kind of sensor deployed at a different application or at a different location. Previous work has shown that if the collection is done with low infrastructure and low power consumption, then environmental distributed monitoring is possible even in remote locations.

However, maintenance of the data quality and capitalizing its use must be taken into account due to different challenges, including data integrity. Nevertheless, data can also be computed and checked through virtual sensor examination and also through model-based statistics estimations. Emerging technologies also indicate the potential of estimation through machine learning interfaces, deep learning, neural networks, and artificial intelligence.

7.3.2. Analytics and Visualization Tools

Nowadays, the emphasis is more on converting the data collected in interconnected digital environments into insights to act. Through advanced techniques such as analytics, the raw data points are transformed into usable and highly actionable knowledge, which can provide the information that organizations can act on in near real time. Those actionable and real-time insights include information about how the assets are performing, maintenance that needs to be performed, and energy usage to be optimized. There are three types of analytics: 1. Descriptive analytics: interpretation of recent historical data to better understand changes that have occurred in the organization. 2. Predictive analytics: information about what will happen in the future, based on what is happening now. 3. Prescriptive analytics: information about what should be done at every step of the way to optimize asset efficiency and to reduce energy waste.

Visual analysis gives insight into the dynamic design as well as how well the system is working. SPM analysis sometimes integrates the design and operation of the system. Visualization lets the user know about the interesting physics and behavior in complex systems. Visualizations can provide consensus building among team members and a means to engage others who might want to learn about the project. There are various visualization techniques to represent the underlying data and the analytical results. Various industry-standard tools are used. A data detection and visualization software tool is used commercially to monitor both consumption and power quality. It incorporates various signal processing techniques including Fourier analysis, inverse Fourier transform, decimation, digital and/or traditional filters, random fluctuations or trends, and time domain averaging. A real-time and offline signal analysis software package with a wide range of powerful mathematical and keyboard features is designed to be used particularly in power electronics but could be used for a range of applications that involve processing electrical data. An application to enable asset management in test, measurement, and condition monitoring system operations to improve safety and broaden access to actionable data is available for remote asset continuous monitoring through wireless machinery condition monitoring devices or systems, data connectivity software, and network or cloud-based data stores.

Visualization of the results should be done so it is unequivocal to avoid misinterpretation of the results and to be linearized to attain a good communication impact. When presented poorly or when they are too complex to understand, the datasheets or tables do very little to create impact because the data do not convey anything that engenders an emotional reaction or compels the listener to pay closer attention. A good way to do this is to embed converter design results inside various trends in color-based 3D data charts and 'slice' through them. Good visual presentation can create that 'wow' reaction. In addition, it could help gauge the audience's reaction to the approach if the intensity of the audience's attention is being observed since it directly impacts the amount of 'traction' or 'following' that the work will ultimately lead to.

7.4. Adaptive Learning in Digital Environments

Adaptive learning, within interconnected digital environments, is imperative to create spaces that can learn and improve continuously (Komaragiri, 2024; Malempati, 2022; Nuka, 2022). Adaptive learning systems, those that can evolve based on different factors such as user interactions and environment feedback, have gained recognition. In various theoretical accounts and research literature, various theoretical frameworks suggest support for an adaptive learning model. For example, from a cognitive theoretical perspective, this is supported by work on multimedia learning. In behaviorism, insights suggest that real-time data capture and analysis can influence behavior change. Human-centred approaches such as experiential learning, cooperative learning environments, and reflective learning all suggest that dynamic and adaptable experiences are critical spaces for learning to some degree.

While adaptive learning models have their roots across different theoretical spaces, the ever-changing and evolving educational sphere means that mechanisms to produce mediating technologies that correctly adapt to changing spaces must be a major concern. Importantly, an adaptive learning system recognises the need to be open to a variety of different viewpoints and pedagogical theories so that the framework within which the adapting takes place might be flexible and allow for change. Different educational theorists have made it known that a rigid instructional model is somewhat problematic within learning systems, and working to learning styles and prejudices keeps us from being in the present moment and also remains not being able to be improved progressively.

For these reasons, an adaptive framework must be supported so learning can be expertly fuelled by various differing possibilities, such as by social means, learning theories, or maybe entirely based upon intrinsic human factors, to augment user interactions for learning. In rule-based models, the main aim is to serve the implicit needs of the user by floating content at the right time and level, so activities based around the content can occur at appropriate levels of difficulty, but at a level the user can also accomplish, fostering a sense of learning flow. Adaptive learning focuses largely on interface, such as making interfaces to the learning environment and looking at differences in how information is presented to learners, tailoring learning environments to protect users from becoming overwhelmed who can use the complexity of the interface as a guide to such effects. Having an adaptive system with intelligent parameters allows the means for the user to capture and free data at different conscious and unconscious psychological practice levels, in contrast to other data harvesting methods like catch-all-during-operations and post-capture, allowing an automation of the learning analysis system.

Case studies have the potential to include an adaptive learning model in real-time and interface design, by way of giving the learner the grand illusion of finer knowledge about their progress and practices but also with some details regarding how to maintain that pace. From a managerial standpoint, the vision is created by way of building a multi-method view, using activity theory as an approach, to present clear information relevant to present practices. One of the outcomes of this approach are case studies to showcase a more interactive and responsive digital environment. Key details include greater interaction with the user via graphically illustrating their actions and responses and a greater user-informed product.

Two more case studies showcase the realisation of the system. One is a standalone software package targeted towards a variety of participants and offers a comprehensive real-time representation and evaluation package teaching learners about the complexities of project management. This package immersed the user in real-life Project Management decisions and got them to compete against other teams but also to use facts and figures to plot and plan the project to their respective business objectives. This offers a digital arena where they can adapt to their environment thus creating up to five and will overpower any suitably equipped opponent.

7.4.1. Theoretical Frameworks

One of the basic ingredients of the ability of a digital environment to adapt itself to the properties of a user is the learning paradigms that address underlying learning processes, user engagement, and knowledge allocation issues. The most commonly referred to constructivist learning theory concentrates on the active engagement of the learner in the learning process as a form of gaining new knowledge and performance abilities. Behaviorism and pedagogy expand this approach through the consideration of the pre-existing knowledge of the learner, their cognitive style, learning preferences, and learning strategies. Such theories provide a set of general rules describing how a learning process should be organized and how it is supported.

The main aim of most adaptive e-learning systems is to adapt learning rates, content, and approach as closely as possible to the needs of a single user. The constructivist view on learning as a process of active knowledge acquisition and pedagogy theory, which concentrates on the existing mental constructs of the learners and the possible transformation of one type of knowledge into another, learning strategies, learning ability, and content properties, traditional cognitive models, and descriptions of the dynamics of forgetting and skill acquisition, are closely interconnected with the info-computational field of theory. However, the common use of constructivist and pedagogy terms in the field of educational informatics and computer systems adaptation can significantly shift from the cornerstones of traditional theories. Adaptation in traditional learning process theory is often based on the extension of the cognitive process and sometimes on physical changes in the teaching-learning process. When this is implemented into technology-supported learning processes, the issues of user experience are particularly relevant. In order to reduce stressful conditions, some educational frameworks permit a user not to be adaptive while recording the score for or feedback on the overall performance.

In a rapidly changing environment, with a huge amount of sources of information of various quality and, even in the computer and network technology field, with an increasing number and types of software and hardware available, one can assess the importance of experience and the effect of knowledge retention through multiple repetitions, using a real-time environment for learning. Many of the basic ideas concerning the learning process in dynamic, automated, and AI-supported learning processes were based on some cognitive models of the users. As technology has heavily progressed since the main constructions of these models were developed, there are many reasons to revisit them. However, in many predictions of the development of cognitive and computational neuroscience, one can expect a significant extension of some of the main conclusions drawn decades ago. Whatever the specific direction of development of the model towards more detail, more integration with other models, or better characterization of the general principles, one conclusion seems to be inescapable. Governed, of course, by criteria for selecting these principles, the models would be elevated to well-grounded process models and would be characterized by a close connection with the testable empirical counterpart.

7.4.2. Case Studies on Adaptive Learning

Today, most organizations and educational institutions use digital environments, making it possible to track user behavior in real time. People expect personalized content, especially in learning, when comparing study recommendations from various platforms. We look into three different large-scale initiatives that optimize user engagement and potentially improve efficiency by digitizing the learner. The case studies on adaptive learning initiatives presented in the following are meant to exemplify the current developments in the field. Despite differences in the sectors in which they operate, these case studies demonstrate the versatility of adaptive learning: in providing individualized feedback, in enabling formative and summative assessments, in recommending pathways through different content modules, and in personalized audio-visual and textual representation of content.

We set out the initial motivations and context, the methodology used in the overall digitalization, and the desired scientific, educational, economic, and societal impacts. For every case, we provide a description and a focused evaluation that addresses the implementation of the initiative, the evidence regarding the transformative effect on learners when suitably using the initiative, the evidence regarding the transformative effect being carried onto the organizations' offline practices, a section on learned lessons, and finally a set of practical recommendations emerging from the underlying cases. All cases present unique features concerning the pedagogical and organizational aspects of adaptive learning, most of which are only recently researched or still in the process of being examined. Some negate the results obtained elsewhere in their unique processes for introducing and establishing enhanced digital experiences as the norm in pedagogy and organizational structure.

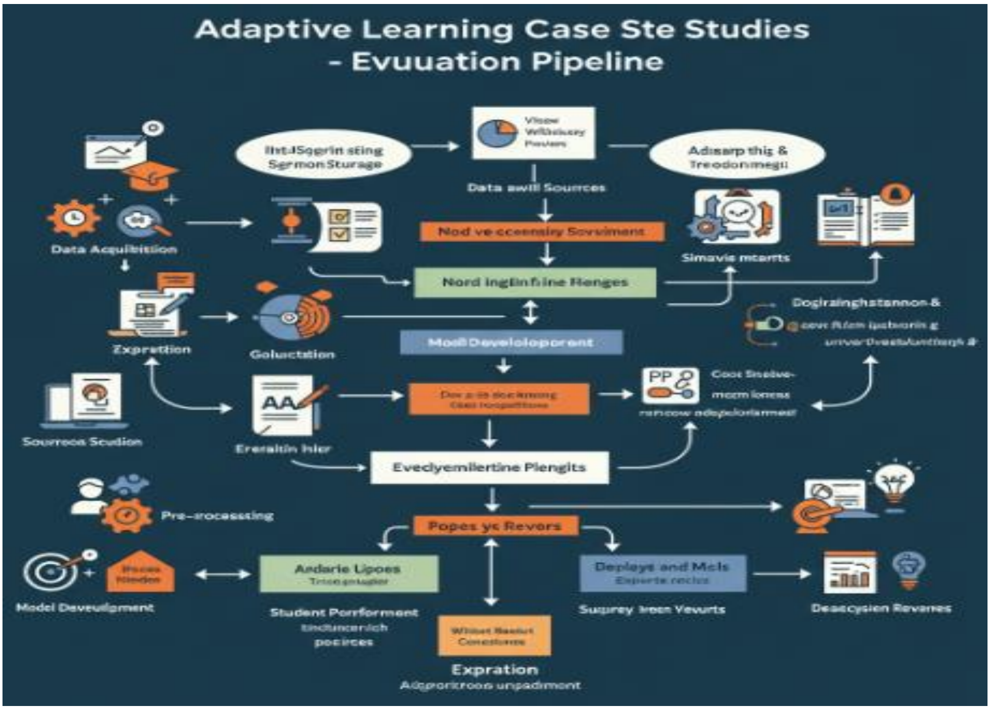

Fig 7 . 2 : Adaptive Learning Case Studies - Evaluation Pipeline

7.5. Energy Optimization Strategies

The advances in machine learning and recent developments in deep learning have resulted in an accelerated deployment of predictive control techniques that can manage buildings, systems, and cities in real-time using large volumes and varieties of data. The weight of digital technologies in optimized energy consumption and generation, which represent significant costs and savings for such real estate and proptech assets, is still often overlooked. Based on a closed-loop iterative learning optimization loop, strategies contributing to improve the balance of energy demands and generation include predictive optimization, anomaly detection, and fault detection and diagnostics of buildings to improve their performance and enhance the value of those assets managed in whole or in part by algorithms.

In the building industry, at least from the office domain perspective, a “zero energy” graduate-level class that encourages a dialogue between all the involved players, along with a net zero energy building conference showcase contest, has demonstrated innovative opportunities for design and deployment. The research conducted towards achieving that zero energy goal is most often focused on either innovative building design, re-design, or smart building controls to improve the optimization of the building operations with maximum comfort for its occupants. None of these domains alone can ensure consistent low energy demand or high energy reusability of a building throughout the lifecycle of the building or multiple generations of occupants using the office space. In addition to those opportunities, which are already significant, interconnected digital environments can help us deliver significant additional performance improvements by optimizing the energy performance of a building, a block of buildings, or an entire energy generation or demand portfolio in real-time.

7.5.1. Energy Consumption Analysis

Buildings are responsible for a large and increasing share of global energy consumption and CO2 emissions caused by human activities. This study proposes and implements a new digital framework that provides real-time information and analysis methodologies for building energy indicators for the academic building and its learning environments. This connected platform was based on the assembly of different interconnected tools that differ in the level of complexity of analysis, the availability of operated data, and their cost.

The use of the well-established evaluation of the building load profile and electricity consumption in combination with the selected energy key performance indicators data was one of the simplest and lowest cost methodologies used to track energy usage in the university academic use building. Once the characterization of professionals and users' behaviors was defined and described, it was possible to monitor and examine the KPI variability in periodic time intervals, and/or as a result of the implementation of control strategies. The results enable a better knowledge of the energy patterns' dependencies on the distinct participative factors and the detected influence of specific user behaviors in academic activities. With society gradually trying to educate about the benefits of digitization and the energy transition, and the need for informed decisions on energy consumption aggregate levels, it is essential to guarantee and implement meaningful information in energy reports to improve a continuous path toward energy-specific sustainable goals for future generations.

7.5.2. Renewable Energy Integration

Increasing dependence on renewable energy sources such as solar and wind to power large-scale data centers can impact availability, effectiveness, and real-time economic procurement of the needed electricity. We present a decentralized, data-driven technique for integrating these resources with large-scale distributed demand, which is driven by workloads and heat recapture opportunities. We show that intermittent profits from reselling power back to the grid can offset the higher up-front cost of the renewable resources, enabling the use of these resources, all while satisfying the data center power budget and time-of-day electricity price requirements. We demonstrate the benefit of such an integrated design over a traditional scenario, where electricity for the data center is procured solely through the grid. Based on power and wind/solar data, we demonstrate the benefit obtainable using real-world renewable resources. Our method can be adapted to other large-scale distributed demand resource integration problems in addition to green data center operation.

To minimize individual and societal impact of these data centers, we have been developing digital environments for demand-driven real-time optimization, insight discovery, and supply support. Here we go a step further and consider pushing the digital environment out to include green, renewable energy sources such as solar farms and wind turbine fields situated near the data centers. Our problem focus is the challenge that the renewable energy sources are intermittent and in general in conflict with supply requirements of the data center. Data centers must stay within their electricity budget, scheduling budgeted decreases in demand for the shoulder times, tempered by the slowdown in task execution they may cause. All electrical supply, whether provided by the grid or by renewable resources, has a price that depends both on time of day and the dynamics of electricity supply. For example, commercial-scale solar power provides relatively flat output during peak demand time of day but can degrade due to fast-moving clouds. Additionally, renewables also affect other electricity markets. For our data center embedded in an energy community, we consider the opportunity to make some profit from time to time by selling the extra renewable power back to the grid when it is abundant and the energy prices are high. In addition, we examine the ability to buy electricity when the price is low.

7.6. Intelligent Infrastructure: Key Components

Choosing the right fuel in an interconnected digital environment requires fast feedback loops based on a sensory feed of the world. Infrastructure that enables fast feedback, a critical part of any system, is taken for granted when it is reliable. Of course, there is a lot more to choosing the right fuel than infrastructure, but it is a key piece of enabling all the data-driven decision-making that represents exciting possibilities for the near future. The supply chain that directly senses and processes data flows and decides next actions is the important second part of the puzzle. But infrastructure provides the data, and that’s what is outlined in this section.

The components: sensors and Internet of Things devices comprising cameras, temperature sensors, microphones, air particulate sensors, glass breakage sensors, motion sensors, LIDAR; data communications networks consisting of cable modems, twisted pair connections, fiber optic connections, cellular connections, Wi-Fi wireless connections; data processing technologies driven by data analytics systems using quotient filters, bloom filters, PCA and ICA, packing and network optimization, digital signal processing, CNN acceleration. These components feed data to analyses of physical abnormalities like glass breaks, gas leaks, gunshots, or explosions or machine anomalies that serve to maximize human comfort while minimizing energy usage. Robust data storage solutions are needed, especially for cloud computing uses, so data storage technologies must be considered. These technologies can use relational database services, storage on Elastic Block Storage, or image data on Elastic File Service, or time-series data on TimeStream, database hosting on open source relational database. Data is of no use while being collected because of its limited scope during real-time analysis. Making sure that data is treated with the right infrastructure and plug-and-play functionality will make sensors and data accessible and scalable like they have never been before. Finally, the infrastructure needs to have the capability to be implemented alongside in-use infrastructure and wiring in communicating with these in-use infrastructure systems to enable successful plug-and-play use cases. The combined need for these data-infrastructural improvements should be a primary goal for anyone operating in an interconnected digital environment. Some of these technologies have been running for a significant amount of time, and we have found success and progress.

7.6.1. Sensors and IoT Devices

Sensors and IoT devices are critical to creating the intelligent infrastructure needed to deliver an interconnected digital environment. Continuous collection of data and real-time insights from these connected sensors and devices have enabled richer experiences around us. One of the most significantly affected fields is that of Environmental Monitoring Systems (EMS), in which real-time data is required for critical decision-making. A major application right now for building energy management is predictive modeling to yield energy comparison, efficiencies, and insights. The same model has been proposed for resource monitoring and control with the inclusion of a soft sensor approach that correlates data between different types of devices. This shows the role of IoT in real-time context adaptation for next-generation IoT-EMS. Hundreds of meters have been deployed in large infrastructures such as healthcare facilities, airports, and commercial buildings. Smart meters are capable of logging data on a per-second or per-minute basis.

There are many types of sensors with specific applications. They can provide data on a plethora of different factors, such as temperature, pressure, humidity, occupancy, and even have counters to count the number of people entering buildings. These sensors are placed in strategic locations throughout the building, and even in each office. Environmental sensors collect raw data and send it wirelessly to a local gateway. These sensors have been developed to work with the existing network infrastructure in buildings, forming a large-scale wireless body area network using IoT technologies. The main differentiator of IoT is its network connectivity. When your devices are connected over a network, that means they have the ability to communicate with other devices; we are no longer disconnected from the people who can offer us services based on the context they are actually in. However, the key challenge with these sensor networks is the security threats they impose. Technologies should develop key identity checks and enhanced security protocols to prevent attacks, malicious packet injections, and data integrity compromises. Modern sensor technologies can and will most likely become more efficient, smaller, and cheaper, ultimately leading to an ever-decreasing amount of energy to transfer, thus saving power. The main advantage of smart sensors is that they are plug and play – this means they can easily be installed, maintained, and replaced. They have the ability to maintain a low bit rate with reduced interference, packet loss, and latency, which is a necessary requirement in critical infrastructures. In order to bridge the gap and demand from new smart sensors and the current legacy infrastructures, it is plausible to rewire existing infrastructures with Ethernet cables. This would add and connect the sensors to the system via gateways. All such developments in smart sensor and IoT technology provide novel and groundbreaking real-time application deployment within smart buildings.

7.6.2. Cloud Computing and Data Storage

Cloud computing and storage have revolutionized IT infrastructure, providing a wide range of service models including development, testing, and deployment models. Cloud solutions allow data storage to be scaled according to data volume and also provide the best opportunity to enhance real-time data availability. Sharing can be increased by third-party sources across various regions and global systems, thus developing a collaborative system. There is a continuous increase in digital content in the next decade, and experts predict an annual doubling of digital bytes every two years. This shows that huge data volumes might force the data to migrate towards cloud storage facilities and advance the need for a seamless creation of data. The data retrieved from numerous sources to the cloud is liable to extend data sharing and collaboration through data analysis and optimization. Numerous novel technologies, applications, and solutions have been developed in the cloud to satisfy those purposes through internet accessibility tools, application processing tools, and data analysis tools that make cloud computing a highly collaborative environment. Cloud computing is highly effective for massive data analytics and some predictive models.

Despite these advantages, data security, privacy, and access control from unauthorized users are inevitable concerns in cloud systems, and several techniques have been proposed to enhance data privacy and security. Storage with cloud solutions is ineffective if it fails to provide real-time analysis, collaboration in solving the energy crisis, and optimizing data for centralized cloud storage systems. The addition of edge computing with IoT devices aids in data reduction, real-time analysis, and shorter latencies for reliable decision-making. As the need for storage is growing exponentially, there are many reports available to optimize data storage with various parameters including performance, cost, and scalability for efficient data search, retrieval, and hierarchical data placement. However, at the same time, a few challenges are raised for the cloud system to manage, as they have little data storage costs between the cloud and data center and also higher access time due to data storage in this cloud. It is highly emphasized, and attention has been paid to consume energy in storage devices with high capacity, which are used in number, and also provide real-time fast access to storage. Such systems are termed energy-efficient computing. More researchers work on designing energy-efficient data storage systems, hybrid systems, and disk array systems, where the main focus is to work on the energy domain for various I/O operations. Thus, for an organization to select the best possible solution for data storage, various designing entities have to be kept aside while choosing an infrastructure setup or a hybrid storage system. In short, with the above-discussed topics, more emphasis is now laid to tailor a system that has both advantages combined into a single domain with lesser drawbacks on the optimization of energy consumption as well as cost-effective data management.

7.7. Interconnectivity Challenges and Solutions

Today, in reality, industrial and commercial digital environments are efficiently isolated concerning applications, operational and environmental data, providing valuable insights from those different data sources. There are various reasons for this: both data and true information can systematically be stored in silos; such systems can be incompatible and/or operated by different entities; various barriers exist, such as stuttering communication, privacy and availability issues, or varying legal jurisdictions; or finally, those systems simply were built on an incompatibility basis with closed standards. However, it is widely recognized that creating such connectivity is desired because there is a need for integrated total solutions that combine different data sources to extend the capabilities of specialized applications with new functionalities that make use of all those data sources to provide and make operations more efficient, safer, secure, and sustainable. Similarly, there exist many digital solutions existing on dedicated software that are not yet interconnected and operated independently of each other, generating opportunities for additional savings. To change this, agnostic platforms were developed that operate independently of the hardware facilities being used and offer standardized Application Program Interfaces that can be used and developed further for integration with other digital tools developed by others. A particular challenge is that the combination of the different platforms must include dealing with change management, procurement handling, operator and user training, and ultimately user acceptance. Further, there is a strong regulatory and operator focus that currently requires a clear breakdown of the costs for one function, i.e., market facilitation, operation, maintenance, and integration.

7.7.1. Data Security and Privacy

Protecting data is essential in any digital environment, especially if the data contains sensitive personal, financial, and other information. Data protection is even more crucial when dealing with real-time data exchanges in interconnected digital environments due to the presence of a high volume of network nodes and communications. One of the scenarios prone to security breaches and cyberattacks is energy optimization through data analytics, especially when the communication involves Personally Identifiable Information. Real-time insights based on internal or external data require the opening of communication ports through organizational firewalls to enable connections to supplier and customer IT systems. Any weaknesses in the processes, infrastructure, and data handling procedures may lead to unauthorized access or data leaks. It is not only possible to anticipate and mitigate the data protection and privacy threats on the basis of standard security controls. A delicate hand on it and requirement-specific secure data science strategies are needed to govern remote access, data exchange, and real-time collaboration between distributed yet interconnected IoT platforms.

A number of security issues are associated with accurate real-time data exchange, from data breaches by hackers, data encryption and decryption, to sharing vulnerabilities between different interconnected systems. Preventive and corrective strategies are available that can enhance data security levels when dealing with interconnected digital environments. For example, encrypted exchange of compressed data on demand with key exchanges for emergency operations could lower threat levels. Additional safety protocols on physical access control could minimize risks by reducing unauthorized access to servers and trusted partners' systems. Legal compliance with key regulations has to be followed by trading sectors. Regulatory compliance is a hot topic, especially for industries. This is due to companies having to find the right balance for insights already existing while protecting the privacy and legal rights of all. There are a plethora of case studies regarding potential privacy and security breaches. This is because of the number of hacks and privacy case studies available.

7.7.2. Interoperability Issues

As digital representations of the physical environment are deployed by various service providers, manufacturers, and residential and commercial building occupants, a key issue is their interoperability. Interoperability, however, means more than just achieving an agreement on protocols at each layer of the communication stack for the transmission of data, including time synchronization and cybersecurity protocols. Interoperability here is defined as a framework to bring together disparate and isolated digital islands into a coherent environment necessary to enable their seamless and self-adaptive collaboration in the operation of modern transactive energy systems. Interconnected partners need to speak a common language, to use a common procedure to follow, and to be able to share information in a format that could be understood in such a way that it can be utilized seamlessly by intended collaborating partners.

The lack of effective interoperability hinders the exchange of data and services among digital environments, slowing down the pace of data monetization, decreasing the overall economics of digital-first business and service models, and impeding the effectiveness of the possible distributed optimizations of cooperating ecosystems. The drivers of interoperability are, on the one hand, technical, driven by multiple standards created across and within countries and different industries by a variety of standard bodies, and the fact that a significant portion of applications and platforms worldwide is based on proprietary technology. Also, the lack of consensus on technology-independent infrastructural requirements for enabling effective operations at the physical sites is one of the barriers of this dimension. It includes requirements for on-site architecture, services, management, and interface requirements; these should be harmonized internationally. The biggest barrier to this sharing is the large amount of unstreamlined data owned by various stakeholders.

Various solutions have been developed or proposed to deal with obstacles to interoperability and improve communication among different digital environment partners and services. Some researchers argue in favor of open standardization. This approach creates advantages for maintaining cooperation from key players. Middleware solutions are other promising solutions for connectivity. For example, one service could communicate with another service in a different digital environment by using a conversational compact messaging service. Some successful examples of initiatives have been taken in various domains to secure interoperable data exchange and program execution between independent domains. A significant push towards standardized interoperable digital representations that spread across geographic locations with the help of a blockchain has been presented. Overcoming interoperability issues is a necessity in order to achieve energy optimization and self-adaptation by leveraging the powers and capabilities of all connected assets in digital environments.

7.8. User Experience in Digital Environments

User experience (UX) is a critical aspect of interconnected digital environments that promotes long-term engagement with the ecosystem at both hardware and software layers. It is influenced by the overall hardware and software architecture, including the design of physical sensors or edge devices and accessibility of software APIs or apps that enable data exchange, AI/ML-based intelligence provision, and interactive control over a Personal Energy System (PES). Factors that condition the quality of UX encompass the design of user interfaces (UIs), accessible user experience (aUX) in the context of design-for-all, and overall engagement experiences enhanced by accessible digital storytelling, behavioral nudges, and implicit coordination with peers. User-centered design efforts and powerful AI and data analytics are needed to make UX intuitive and the technology robust and effective in providing good real-time and predictive decision support. In a well-designed system, feedback related to user preferences measured through physical interaction data triggers relevant digital environment services that maintain longevity of use.

The effectiveness of an intelligent digital environment in achieving energy savings, user well-being, and environmental benefits is influenced by the ability of the technology to reach and engage users. Systems that use personalization strategies to induce desired actions and habit formation in large user bases are more effective and have a wider reach and positive effect. Individual UI customization that is different for every user improves perceived UX but is very inefficient to design and maintain at scale. The increasing level of anticipation of digital environments and the expectation of transparent orchestration that evolves contextualization into a particular, localized event prepared and might trigger different systems in a short span also adds challenges. Unsatisfactory UX, including trust, of any digital environment may turn users off, negating possible system effectiveness gains.

7.8.1. User-Centered Design Principles

The effectiveness of digital environments is proportional to how well they match user needs and behaviors. Because of this, design decisions need to be grounded in insights, which can be chronicled and shared with others. In this subsection, we focus on those methods of requirements gathering that enhance the usability of the outcome in life cycle terms. There are two possible approaches when employing user-centered design principles: build from sources that gather user feedback, making design an iterative process, which is a pragmatic approach. Or, create digital environments that cater to as wide a user group as possible from the outset by encapsulating generic and adaptable technologies in different interfaces, making the above process essential - an academic approach. Both approaches can translate feedback, whether user preferences or levels of generated network traffic, into refined practice in a legitimized way.

Inputs to digital environment design can come from internal experience and good practices used by other trust and organizational digital environments and genuine insights gleaned from interviews and usability testing. In terms of this subsection, these insights tend to be deeply held requirements of users that cannot be met in any other way; hence they form the starting point for us when considering engine requirements. The need to iterate the design process will be reasserted later in this chapter as a key quality in the design engine - the need to adapt the process based on user feedback, and the ability to do so with ease. Conducting and reacting to thorough requirements analysis and emphasizing the ease, simplicity, and accessibility of interfaces are strongly linked to the success of the existing digital environments in both academia and industry. Ensuring an iterative design process that responds to feedback is arguably even more important.

7.8.2. Feedback Mechanisms

In digital environments, feedback mechanisms can be used to support users by providing a better understanding of the current state of the system. In general, different types of feedback might be available, such as user ratings or other performance measures. However, a deeper understanding can be derived from actively inquiring the user for feedback – this might be in terms of ratings, but even behavioral analytics or direct user

Fig 7.3: User Feedback Mechanisms in Digital Environments Outer: Usage Frequency | Inner: Effectiveness

input can provide valuable insights into how users perceive and feel about a provided digital environment. These insights can then be used to drive improvements iteratively and gradually increase the overall user experience and, subsequently, user satisfaction. Additionally, feedback can also be used as a means for increasing acceptance and to jump-start a successful operation of digital environments. However, a guiding principle needs to be adhered to – users should only be queried for feedback at moments when they have valuable information to share, and when their experience is still fresh in their memory. In addition to formal feedback collection, feedback can also be acquired in a more informal way. For instance, iterations over prototypes can be evaluated through usability tests and via user interviews.

Challenges also arise when working with user feedback. Quantitative values such as higher or lower satisfaction might not always paint the whole picture, and any decision based on this requires careful consideration. Also, the collection of valuable qualitative data through open-ended questions may introduce bias; thus, their interpretation requires much thought and is often a manual task. Decisions need to be informed, in particular, by a holistic view of multiple data sources – looking at depleted feedback data collected in different ways and not relying on a single source such as rating averages. It is paramount to establish a feedback culture. Users need to be incentivized and motivated to submit honest and open feedback and be informed about any actions or decisions resulting from collected feedback. Feedback on individual facilities is used to continuously improve the environment and learn from the collected data.

7.9. Conclusion

Rapid access to real-time insights has become an increasingly pivotal topic for research, especially in connection with the deployment of flexible energy consumption. While a deep converging digital landscape adds to our toolbox to address these challenges, interconnected digital ecosystems also pose major challenges. In this essay, adaptive learning, intelligent building infrastructure, and the impact of personalized user experience on energy consumption in a digital ecosystem are highlighted. While few best-in-class showcases are already in operation, many areas of interconnectivity optimization across technology, sensors, software, data structures, and actionable decision-making, as well as user behavior, remain to be explored. The next big step, in order to enhance the digital ecosystem concept and logic, is a set of communicative–collaborative–cooperative digital ecosystems. Interconnected digital environments are no longer a promise of a distant future; they are increasingly shaping our present reality and promise to be part of a tech-driven transformation. Growing interest in the area is reflected in some of the initiatives and projects undertaken by various institutions as well in other public and private activities. However, many challenges remain, such as enhancing the connectivity between digital environments and data-driven decisions. Moreover, this is also a question of the overall acceptance and attractiveness of the smart campus. At a society level, we will be able to create cities that are energy-efficient and sustainable only if we will be able to establish an interconnected digital ecosystem among different stakeholders; including citizens and policymakers, across different urban infrastructures. The digital revolution offers unprecedented opportunities and it is our role to design this interconnected digital environment in such a way that it remains an inclusive and collaborative one. The digital ecosystem should offer a framework where region's stakeholders design cross-fertilization models that drive all the region towards energy efficiency. Only in this way can we assure that these ecosystems transition toward a future that is socially attractive; and that is linked to thriving and happy communities.

7.9.1. Final Thoughts and Future Directions

As energy prices are forecasted to rise in the future, organizations are becoming more cognizant of the fact that real-time insights can make their energy management practices more effective and efficient. New technologies, such as IoT, cloud computing, big data, and advanced machine learning algorithms, are capable of generating these real-time insights. If organizations work toward integrating their digital environments, they will discover new possibilities to optimize their energy use or the wider supply chain, resulting in considerable cost savings, especially for large organizations. In order to improve our insights, more extensive research should examine which new technologies and frameworks can be implemented to optimize energy use. In conclusion, we believe that ensuring proactive engagement with organizations over innovations they could aim for to aid in the marketing and practical use of their approach is crucial to the ecosystem. The appetite and capability to innovate and adapt in organizations is something that can provide a competitive advantage. It will also be significant to consider the interests of users to carry out the required social change and promote energy saving proactively. Work in this area can also contribute to the major trends in energy systems, including decentralized models and artificial intelligence, that may change the current position in energy use management. Any research in these areas can deliver valuable insights.

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