Smart Homes

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Abstract

As a result of increasing technological advancements in sensors, internet connectivity, and data processing and analytics, a new industry sector has emerged, which connects these areas to create automated tasks. The Internet of Things (IoT) is a critical field that is now considered the fourth industrial revolution and has the potential to become one of the most influential developments in automation. This paper focuses on the application of IoT technologies in individual households, known as smart home environments. It examines the theoretical foundations behind its functionalities, including its history and concept, to establish a foundation of what the sector offers and identify potential users. A comprehensive review of the major technical aspects identifies the devices and technologies in use and their applications in energy efficiency, connectedness, data flows, and storage. Additionally, a study of the analytical aspects of the smart home industry facilitates discussion regarding the technology ecosystem's purposes and objectives, as well as its main adoption barriers such as costs, reliability, and security risks.

Keywords: Smart homes, smart technologies, Internet of Things (IoT), analytics, optimization, prediction models, and security and privacy

Contents

1 Introduction

Throughout the world, there has been an ever-growing popularity of convenient and accessible technologies that has granted evident benefits to consumers. The domain of home automation, or domotics, is no exception to this phenomenon. In the last several decades, there have been multiple drivers that contribute to the smart home technologies development. For instance, the willingness to reduce and optimize energy consumption, or the individual's wish to have more control over their home that have the potential to maximize their comfort and overall lifestyle (Balta-Ozkan et al., 2013). Distinction can be made between a traditional home and a smart home as explained by Balta-Ozkan et al., 2013: "today, the "traditional home" has appliances that are operated locally and manually, usually by flipping a switch or pushing a button. These devices have limited controls and managing energy use can be difficult. The smart home, on the other hand, allows for remote electronic control and management of smart appliances (heaters, air conditioners, washing machines, etc.) and represents the convergence of energy efficient appliances and real-time access to energy usage data, facilitated by a network of sensors and computers." This interpretation highlights some of the key components of the smart home concept:

- Automation of tasks: Automation frees the user from executing said tasks themselves. Depending on the level of automation and the type of task, the user might not even need to monitor it.
- Communication between the diverse actors: In contrast to a traditional home, appliances are not an insulated entity, but connected to a network which allows for a dialogue between them and other sensors, devices, services, or the user. This creates a connected product which is more than the sum of its parts, as it aims to work as one coherent unit.
- Collection and analysis of information: In contrast with a traditional home, a smart home collects important quantities of data and allows for measurements which are much more precise than in a traditional setting. To help the user, smart homes need to solve optimization problems, for example to reduce energy consumption, or to create predictive models to forecast behaviors, such as the time homeowners usually use their coffee machine. This means that the smart home has to perform various analyses, but to do so, it must gather, store and manage data.
- Access to control and information: Linking to the concept of a smart home as one network entity, this network has to provide its users as much control and information as possible in convenient ways (Balta-Ozkan et al., 2013). This often takes the form of dashboards, interactive displays, or apps on the user's smartphone.

These elements provide a better understanding of what a smart home is. However, the concept is very vast and deserves to be properly explored.

1.1 Smart Home Definition

When describing modern domestic technology, phrases such as ”connected home”, ”intelligent house”, or ”home automation system” may lack clarity or meaning. To ensure that there is a global comprehension of what these expressions encompass, this section outlines the definitions of a ”smart home.”

Scholars have defined the concept of ”smart home” in multiple ways, showcasing the broad range of terms used to describe it. Some have characterized smart homes as a residence equipped with a high-tech network that links sensors with domestic devices and appliances while providing services that meet the needs of the inhabitants (Balta-Ozkan et al., 2013). Others have highlighted that a smart house uses diverse communication methods and optimization algorithms to forecast, analyze, optimize, and regulate their energy-consumption patterns based on predetermined user preferences (El-Azab, 2021). Furthermore, home systems are mentioned to efficiently manage a wide variety of home electronics, including audio/video, security, lighting, and HVAC (Aldrich, 2003). If these devices are consolidated into a main control system, residents can gain insightful information about their electricity habits. As technology continues to progress, occupants can access their data from remote locations, allowing them to supervise their consumption and control their household systems and gadgets. Some writers have even examined these systems and devices further by concentrating on how these entities utilize integrated technologies such as Internet of Things (IoT) (Moniruzzaman et al., 2020). Smart homes and their networks are built on the concept of interconnecting devices to enhance the quality of life. By incorporating advanced technologies and communication systems, it becomes effortless to optimize energy usage and create a better quality of living.

1.2 History of Smart Homes

Over the span of two decades, the popularity of the ’smart home’ concept witnessed a significant upsurge. As individuals became increasingly conscious of the potential cost-saving benefits and the enhanced energy control through automation, the adoption of such powerful innovations became more appealing. However, this transformative shift was not an overnight occurrence, as it can be traced back to the 20th century when the introduction of electricity into private residences enabled homeowners to upgrade their conventional domestic appliances (Aldrich, 2003). Prior to this, the notion of a smart home was inconceivable. Electricity brought forth a new and convenient source of clean power for appliances, and this in turn prompted the development of innovative equipment for household use. (Aldrich, 2003). Nonetheless, it was not just the introduction of electricity that played a role in this evolution. From 1975, information technology gained momentum in the market by facilitating the exchange of information among people, appliances, systems, and networks in and beyond the home (Aldrich, 2003).

Comprehending the historical trajectory of domestic technology is important to understand society's current standing. Undoubtedly, household appliances have modified our daily lives. From using smart devices to wash and dry clothes to programming espresso machines to prepare coffee at a specific time, these advances have streamlined routines. The origin of these concepts can be traced back to pivotal milestones that began in the early 1900s. Around this time, emerging middle-class households experienced a shortage of domestic servants and electrically powered machines became widely accessible (Aldrich, 2003). Therefore, maids were no longer a necessity because these advancements in domestic technologies allowed one person to manage the chores and pursue other interests outside of their home. Specifically in the United Kingdom by 1940, most residences had acquired electricity, which surprisingly increased the time occupants, typically women, spent tidying up their home than ever before (Aldrich, 2003). In addition, the aftermath of World War II marked another significant event before the concept of a "smart home" truly gained prominence. This shifted women's roles from housewives to tech-savvy businesswomen, resulting in homeowners remodeling or constructing kitchens to equip them with the latest and greatest appliances for ease of use. Even television sales increased due to of the emergence of home "television lounge[s]" (Aldrich, 2003). Between the 1960s and 1990s, homeowners were introduced to leading-edge technologies such as central heating, thermostats, mobile phones, and entertainment systems (Aldrich, 2003). During that period, a singular machine achieved the connection between homes and external information: the personal computer (PC) (Aldrich, 2003). This monumental invention enabled internet access, and the PC facilitated connections to numerous services like banking and shopping from the comfort of one's home (Aldrich, 2003). Although the adoption of these machines occurred at varying rates and under unique circumstances, they collectively contributed to the emergence of a 'smart home' concept.

1.3 The "Smart Home" Concept

In the film "Smart House" released in 1999, screenwriters William R. Hudson and Stu Krieger crafted a remarkable piece of work that illustrated a futuristic vision of a computerized house. Throughout the movie, the story depicts inconceivable scenarios that portray technology as fully automated and interconnected. Notably, the protagonist, Sarah Barnes, designed a voice-activated virtual assistant called PAT (Personal Applied Technology) that controlled every aspect in the residence ("Smart house", 1999). While dining, inhabitants could summon PAT to activate interaction holographic projections that displayed different environments ("Smart house", 1999). Other examples of intelligent technology portrayed within the film were automated cleaning robots and smart mirrors that offered fashion advice and skincare recommendations ("Smart house", 1999). Although some of these technologies still may seem improbable today, they could be rapidly approaching. During the 1990s, "Smart House" was one example that gained immense relevance as it helped mark the emergence of the 'smart home' in popular culture (Aldrich, 2003). Additionally, magazines and documentary producers began exploring this new technological frontier. A television series, ”DreamHouse,” depicted the experiences of a family who resided in a cutting-edge intelligent home for a six-week duration, enabling the audience to envision what it would be like to live in such a place (Aldrich, 2003). This demonstration illuminated the fact that smart homes were no longer science fiction but were slowly becoming reality.

The emergence of smart homes as the latest trend was not solely attributed to the prevalence of screen entertainment. Rewinding back to the 1960s, numerous labor-saving devices became common household items, including hair dryers, electric razors, vacuum cleaners, etc. (Aldrich, 2003). Since these gadgets were entering more residences, the interest in expanding electrical wiring in one's homes for increased functionality was desired (Aldrich, 2003). However, it was not until later when commercial entities, like the National Association of Home Builders (NAHB) in the United States, embraced this concept due to various technologies and appliances that would now be incorporated into newly constructed homes (Aldrich, 2003). Between ”time-saving” and ”time-using” products, a need for a more efficient approach to connect multiple devices by electrical outlets was required. ”Time-saving” products such as washing machines can help reduce the time required to complete a task, thereby increasing discretionary time, while ”time-using” goods like televisions consume discretionary time but can enhance its perceived quality (Aldrich, 2003). These technological advancements were being increasingly accepted and the NAHB established a special committee named ”Smart House,” advocating for the incorporation of necessary technology and automation into the design of new residences (Aldrich, 2003). The evolution of smart homes from a futuristic concept to a tangible reality can be attributed to various factors, including the portrayal of intelligent technology in mainstream culture and the desire for more efficient and connected homes. As the line between science fiction and reality continues to blur, smart homes are poised to become the standard for modern households.

1.4 Smart Home Users

The purchase rate of smart home technology continues to prosper as the demand in the consumer market increases, which is evident from the significant rise in households that have incorporated at least one IoT device (Cvitić et al., 2021). This trend indicates promising prospects that will integrate smart technology into their domestic settings. Moreover, the impact of IoTs extends to a wide range of individuals who intend on acquiring and implementing such gadgets into their daily routines.

A study conducted in Malaysia stated that their younger generation and those with higher education are more inclined to use smart homes (Rock et al., 2022). This outcome is unsurprising, given the limited availability of IoT applications that left many people unaware of such technologies, as pointed out by Rock (Rock et al., 2022). Charlie Wilson further noted that prospective smart home users tend to be interested in information, price-response, and rational in managing domestic energy use (Wilson et al., 2014). The author further classifies smart home users into several groups, including the incremental home improver, low- and middle-income households, high-income technophiles, and women, children, and families who belong to a socio-technical framework that elevates their usage above that of a unitary household (Wilson et al., 2014). The research also emphasized the importance of recognizing gender roles and identities during the technological design and development process that women and children are anticipated to become prominent smart home users (Wilson et al., 2014). While this list may seem extensive, it is worth mentioning another noteworthy demographic that warrants consideration: the elderly in smart community-based retirement living.

Although this research paper will not primarily focus on assisted living facilities, it is important to understand the factors that determine the usage and significance of smart home IoTs. The literature on this topic alone is quite extensive. Hence, this paper will briefly highlight the vital aspects. According to an article entitled "Smart homes and their users: a systemic analysis and key challenges," assisted living homes differ significantly from conventional homes, as they prioritize active ageing, independence, self-determination, freedom of choice, and changing and inter-dependent needs of an elderly population (Wilson et al., 2014). Smart technology in adult care homes allows their residents to access emergency assistance, receive help with hearing or visual impairments, and have automatic systems which detect and prevent falls (Wilson et al., 2014). These services are integrated into various products, such as wearable and implantable devices that monitor various physiological parameters of patients (Wilson et al., 2014). Most personal care homes incorporate these components to enable their guests to live stress-free and feel secure living in this safe environment.

The implementation of smart home technology has been driven by the desire for convenience, safety, and affordability, making it extremely advantageous. The historical exploration of this concept indicates how diverse demographics benefit from these gadgets and will continue to enter the market in search of new products. Armed with this understanding, it is imperative to investigate the technical mechanisms of smart homes.

2 Technical Aspects of a Smart Home

2.1 General Description

A smart home's infrastructure and architecture consist of numerous elements that are all essential for its proper functioning. Our research dives into this intricate system by starting with a thorough examination of the infrastructure. This serves as a prerequisite to understand the physical and virtual components that support an intelligent home. We then proceed to investigate the architectural structures which involve the design principles, functionality considerations, safety measures, and other related aspects. The foundation of a smart home is a complex, interconnected network that performs various integral functions, enabling the home to effectively optimize and regulate its energy consumption.

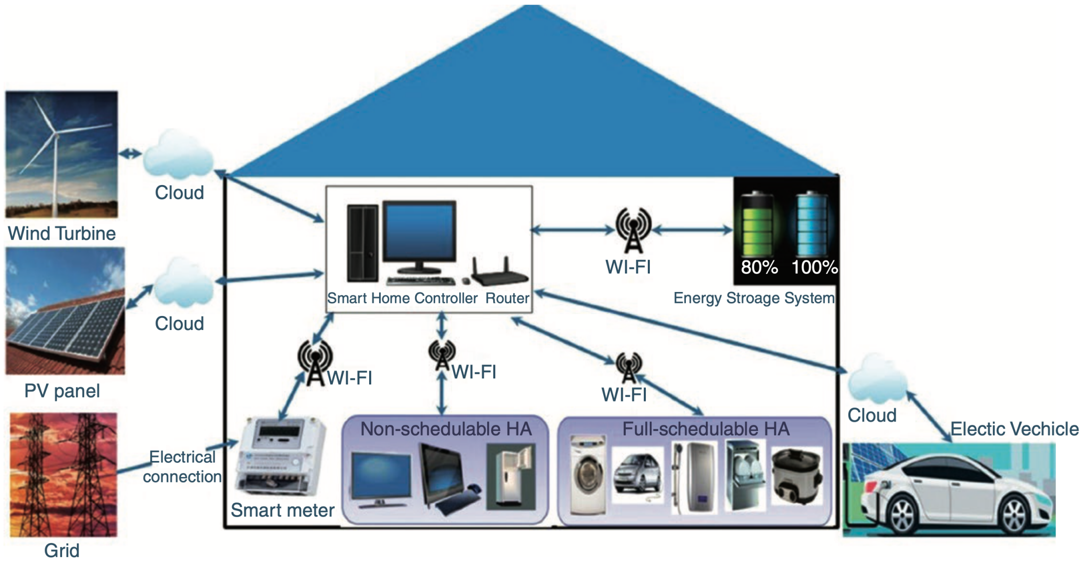

Figure 1: The general infrastructure of smart homes (El-Azab, 2021)

Figure 1 illustrates five aspects, which will be discussed below. However, the primary focus will be on three of these components, namely the control center, smart meter, and appliances.

- Control center: A motherboard that enables a smart home to connect and control other devices and appliances throughout the residence. Through smart-home energy-management systems (SHEMS), the main center should command home appliances and available energy resources according to the real-time tariff and home user's requirements, optimize demand and generation coordination, and verify the predefined objective (El-Azab, 2021). El-Azab explains that there are three objectives that the control center aims to achieve:

  1. "collecting data from different meters, homeowners' commands and grid utility via a proper communication system;
  2. providing proper monitoring and analysis of home energy consumption for homeowners;
  3. coordinating between different appliances and resources to satisfy the optimal solution for predefined objectives" (El-Azab, 2021).

- Smart meter: This technology is a critical element that digitally measures the amount of energy consumed and sends the consumption data to the power supplier without requiring manual interpretation by a field technician (AER, 2017). In recent years, Rasha El-Azab noted that these "advanced smart-metering infrastructures can monitor many home features such as electrical consumption, gas, water and heating" (El-Azab, 2021). This offers several advantages, which we will discuss further in our Sensors and Data Collection section.

- Appliances: Modern-day living involves the use of equipment that performs specific tasks, typically powered by electricity, gas or from another power source. Homeowners have installed these appliances into their homes for ease and convenience. There are two categories of these smart home loads: schedulable and non-schedulable (El-Azab, 2021). Consider a washing machine or air conditioner, they are classified as schedulable since these functions can be on a "predictable operating pattern that can be shifted or controlled via SHEMS" (El-Azab, 2021). In contrast, non-schedulable loads, such as printers or straighteners, operate infrequently according to the homeowner's desires without any predictable operating patterns (El-Azab, 2021).

The other two relevant components focus on electricity resources and communication schemes. Due to the scope of this paper, we will provide a brief overview of these integral parts. Figure 1 on the left depicts the primary types of renewable resources for electricity – solar (PV panel) and wind turbine plants in modern grids (El-Azab, 2021). These are essential in generating and storing electricity, resulting in enhanced home-energy efficiency and reduced costs to homeowners (El-Azab, 2021). Furthermore, the communication schemes in a smart home system extend beyond an Amazon Echo — a voice-activated smart speaker — to built-in components that enable both homeowners and "grid operators to monitor and control several home appliances to achieve the optimal home-energy profile while preserving a comfortable lifestyle" (El-Azab, 2021). To enable effective communication between devices, several communication methods such as Wi-Fi and IoT are utilized. Wi-Fi is one example of a practical way to connect information-based devices and IoT is a more abstract method, connecting home devices, users, and grid operators through the internet to monitor and manage smart homes (El-Azab, 2021). Cloud computing and IoTs have become affordable and user-friendly services that have expedited the widespread adoption of smart technologies in homes, marking the beginning of the smart home era. However, security and privacy concerns arise due to the potential threat of hackers, especially as IoT is compatible with other communication protocols like Zigbee and Bluetooth (El-Azab, 2021).

To establish a successful smart home system, the foundation and architecture are both instrumental. The two types of architecture that exist are centralized and autonomous. The former involves a control center that acts as a decision-making unit by receiving and analyzing data from the different sensors and devices. The control center then triggers the appropriate device by sending messages and instructions, which can be processed either by a cloud application or hardware-specific device (Hammi et al., 2022). An enhanced version of this centralized model is the Software Defined Smart Home, which implements the core idea of Software Defined Networks (SDN) (Hammi et al., 2022). SDN addresses challenges by utilizing smart devices and sensors around the home to aggregate, process, and make decisions. For SDN to be deemed successful, the control center should autonomously manage all the devices and ensure complete integration for personalized services of the highest quality (Hammi et al., 2022).

When discussing architecture, it is important to note that autonomy is not limited to the centralized model but is more commonly associated with autonomous architecture. In this solution, ”each device is fully autonomous in sensing, collecting information, taking decisions, communicating with other devices and acting” (Hammi et al., 2022). To ensure that a device has a complete understanding about its environment, it must cooperate and coordinate with other technologies, which can be remotely accessed or controlled by the homeowner if necessary. Figure 2 exemplifies how this architecture adopts a distinct cloud-based approach through its collaboration through a variety of sensors.

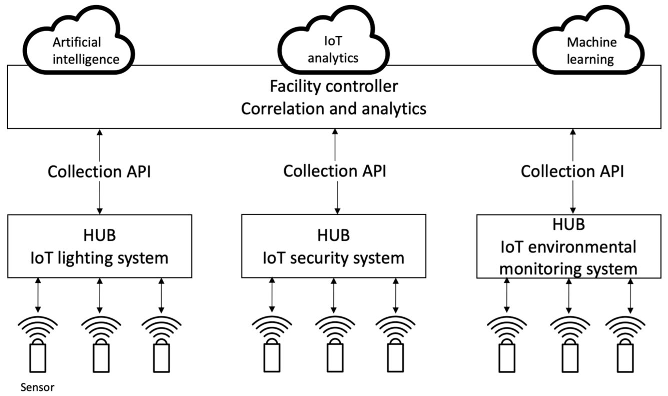

Figure 2: Cloud based smart home architecture (Hammi et al., 2022)

The synergy between a smart home’s infrastructure and architecture is crucial in meeting the inhabitants’ expectations. This collaboration not only enhances convenience and security, but also ensures that the smart devices function appropriately to help reduce energy consumption and minimize costs.

2.2 State of the Art

2.2.1 Smart Home Devices

At the conclusion of 2021, projections estimated that the global smart home market size would surpass $53.45 billion (Moniruzzaman et al., 2020). From 2018 to 2022, the adoption of smart homes continuously grew with a compound annual growth rate of 20.8% (Moniruzzaman et al., 2020). This trend was not unexpected, given the historical context of the development of this technology and lifestyle. With the multitude of smart technologies available, people are becoming increasingly aware of the advantages and disadvantages of incorporating them into their homes. However, consumers continue to enter the market and obtain the latest and most technologically advanced products that cater to their desired outcomes, whether they are homeowners or renters.

As the smart home industry gains more residents, there are different approaches to incorporating technology into their homes. Some individuals may choose to use a single device like Amazon Alexa for playing music or setting cooking timers, while others may opt for a fully automated home with various advanced machines. The underlying principle of a smart home is to enhance daily life through technology, whether you choose to implement a one smart gadget or a fully self-regulated house. Therefore, to avoid confusion between smart home devices and a smart home itself, this paper will briefly outline the similarities and differences between the two.

As the technology behind a smart home continues to evolve, it is essential to understand how these devices impact the overall model. A smart device is a physical object that is comprised of ”sensors, monitors, interfaces, appliances and devices networked together to enable automation as well as localized and remote control of the domestic environment” (Wilson et al., 2014). Some examples include smart thermostats, smart speakers, and smart security systems. The similarities between a smart home and its respective devices are the following:

- Connectivity: Both remotely communicate with each other through the internet.
- Automation: The premise of building a smart home is to ensure the inner workings can act in tandem without the need for human intervention.
- Convenience: Each can be customized to maintain the highest level of quality and satisfaction to meet the residents’ standards.
- Energy Efficiency: Designed to optimize energy and increase cost-savings.

In contrast, there are several differences such as:

- Scope: A smart home is the entire system of devices and appliances that are connected and controlled through a control center, while smart devices are individual components such as a smart thermostat or smart lights.
- Complexity: The integration and coordination between multiple devices and appliances make the configuration of the smart home much more intricate than a single gadget that can comparatively be simple to install.
- Cost: Building a truly smart home can be very expensive as there are various integral components that are required. However, purchasing single devices over a longer period can save money and provide similar benefits.

While a smart home can be expensive and complex to set up, it offers a fully automated system that can save time, increase convenience, and optimize energy usage. On the other hand, smart devices offer similar benefits at a lower cost and can be added or removed from a smart home system with ease. Ultimately, the choice between a fully automated smart home or individual smart devices will depend on the homeowner's needs, preferences, and budget.

2.2.2 Smart Home Technologies and Services

A smart home is a technological and service-based integration that aims to enhance the standard of living through home networking (Kadam et al., 2015). In this regard, a smart service is tailored to the user's needs and context and utilizes data from its surroundings through an interface. It employs artificial intelligence to process tasks and offers at least one advantageous solution to address a consumer's issue (Brill & Nissen, 2022). The objective of these systems is to increase the efficiency of electricity usage in households by effectively managing home equipment to minimize energy consumption, while also generating and storing energy (Fabi et al., 2017). The authors of "Smart Home System" present several home services that communicate between different processes through a main center to achieve these goals (Kadam et al., 2015).

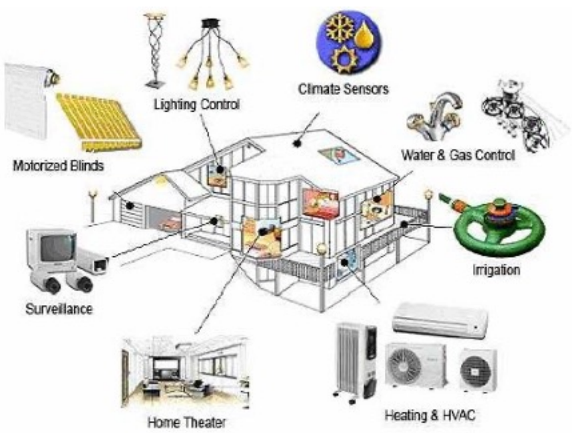

Figure 3: A smart home integration services (Kadam et al., 2015)

Between smart devices and services, these state-of-the-art products overlap in how they integrate into our daily lives. For instance, consider an entry point into a house. A Ring doorbell is a smart device that detects motion at the door, linked to one's smartphone. As it monitors, it collects data using artificial intelligence to provide personalized features like turning on exterior lighting. For this service to occur though, either a central control system or a hub is required. While many devices are wired, smart services are usually wireless. It typically depends on how the smart home was built, from the ground up or in a piecemeal fashion (Kadam et al., 2015). There are five distinct smart device categories that are relevant to the incorporation between smart devices and services: entertainment, environment, security, and communication (Kadam et al., 2015). Within each of those groupings, there are examples in Figure 4 that pertain to how many of these devices can function autonomously, "be programmable (schedulable) or can be remotely controlled through software applications," which provide services such as "comfort and security" (Hammi et al., 2022). Like smart devices, smart services are represented in three groupings: entertainment, security, and energy efficiency (Fabi et al., 2017). A few decades ago, this would have all been imaginable. However, in the world we live in today, anything appears possible with time.

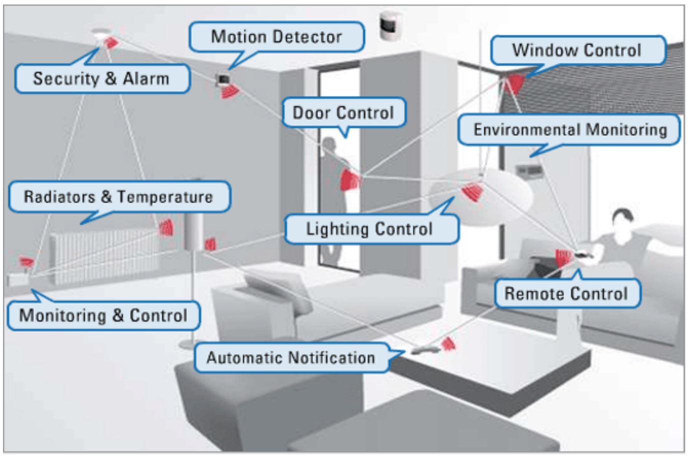

Figure 4: Examples of the smart devices (Kadam et al., 2015)

2.2.3 Experimental Projects

Prior to smart homes coming into fruition, researchers and developers conducted extensive research and experimentation to ensure that products and/or services catered to the needs of consumers. One of the earliest examples of an experimental smart home was the "Dream-House," allowing outsiders to envision what such a house might look like. Apart from this project, various organizations around the globe have overseen several other noteworthy smart home initiatives over the years.

The University of Colorado's Adaptive House was designed to explore the concept of a self-programming home, thereby freeing inhabitants from the burden of carrying out routine tasks (Aldrich, 2003). Researchers focused on monitoring systems to analyze how a neural network could learn patterns and perform tasks automatically without resident input (Aldrich, 2003). A prototype unit controlled various aspects such as room temperature, water heat, ventilation and lighting while also having "sensors which monitor temperature, light levels, sound, the opening of windows among others" (Aldrich, 2003). Similarly, The Interactive Institute's ComHOME was a smart apartment "equipped with technologies such as sensors, voice control and voice-mediated communication" (Aldrich, 2003). The main objective was to investigate "different aspects of home-based activity, exploring the impact of technology on them (Aldrich, 2003).

Finally, the Massachusetts Institute of Technology's House_n project was led by the Department of Architecture. Their overall aim was to create "environments which suit people of all ages; creating customizable environments; developing algorithms to interpret sensor data to detect what people are doing; exploring the impact of technology on traditional learning environments; inventing interfaces and components that conserve resources; and exploring the impact of home delivery of products and services" (Aldrich, 2003). Through these experiments, researchers have been able to share their findings to improve the home equipment functionality. Without such projects, testing and validation would not be possible to bring these ideas to life.

2.3 Specific Topics

2.3.1 Sensors and Data Collection

Introducing new technology into the market can be alarming, but through experimental projects and research, organizations like University of Colorado bring these devices and concepts to life. As smart homes have gained popularity over the decades, advantageous devices such as sensors have changed the way residents interact with their home. As individuals become more tech-savvy and interested in their energy consumption, smart sensors have broken the barrier which allows consumers to automatically collect accurate data. Typically, these sensors are considered "low-profile wireless devices" that detect certain activities. In turn, they communicate to other smart devices on how to react (Pattison Tuohy, 2022). To process that data though, it must first be captured. These detectors are entry points that gather pertinent information for the end-user.

Sensors can be categorized into two main groups: binary sensors and numerical sensors (Ribeiro Serrenho & Bertoldi, 2019). The first type of sensors can detect the presence or absence of an object or a movement through a value of 1 or 0 (Ribeiro Serrenho & Bertoldi, 2019). Examples of such devices used in a smart home include motion detection, pressure, or contact sensors. Motion sensors are used in smart doorbells or smart lighting, while pressure sensors could be present inside beds to detect whether someone is sleeping or not. Contact sensors can sense if doors or windows are closed, which can be part of a smart security system. Numerical sensors, on the other hand, are used to measure quantities. For instance, one of the most well-known devices is a carbon monoxide detector, which records the amount of carbon monoxide present in the air. Other examples include "traditional meteorological parameters like temperature, pressure or humidity or environmental parameters like pollution indexes, air quality, dust or pollen" (Ribeiro Serrenho & Bertoldi, 2019).

There are additional sensors that are utilized within a smart home to collect other data mediums. Consider a Ring Video Doorbell that has a built-in camera. This device allows the owner to see a live video feed at a given location of one's house at any given moment (de Looper, 2023). Essentially, anything that records video footage or can take pictures are sensors that capture visual data. In parallel, most of these devices have a sound sensor. This works in a similar way to how a human processes sound; "it has a diaphragm that converts air pressure vibrations into electrical signals that are conveyed to the computer" (Nair et al., 2021). Although the smart doorbell can detect visual and audio inputs, smart sensors like Alexa or Siri who are known as personal assistants, only capture sound. One type of sensor that has not been discussed is in relation to geolocation tracking. These detectors track position data, which could be relevant to the movement around one's home to control for when to turn on certain lights or turn off the heat to conserve energy. Typically, these sensors are used within a vehicle for direction assistant, like a Global Positioning System (GPS), as GPS technologies have trouble capturing a precise signal when the device is inside a building.

These different sensor categories should not be regarded as fixed or exclusive but as fluid and collectively acting as one unit. They are often used in combination and their responsibilities can overlap. For instance, a numerical sensor, if it is used to detect a response above a certain threshold, can be considered binary. All in all, these sensors play a major role in data collection within a smart home or device and can be applied throughout many applications.

2.3.2 Data Storage

Once data is collected by sensors, it is a necessity to properly store this information in a way that ensures its accessibility, reliability, and security. Since smart homes generate enormous amounts of data, it is essential to survey the different options for storing them. This is a critical aspect of any smart home system, and there are four categories that will be examined: personal storage, private cloud, public cloud, and hybrid cloud (Petrova, 2020).

- Personal storage can be considered as a computer, flash card, or server which belongs to the homeowner (Petrova, 2020). This type of storage is often used for data that does not represent larger volumes. For instance, this information is regularly wiped and replaced, erasing history that does not need to be kept. In addition, a smaller volume of data could be a text file. Typically, smart home technologies have been designed to provide advanced analytics which are then stored using cloud solutions for providers to have access to it. Therefore, personal storage does not require complex analytics either. Personal storage is the most secure form of storage regarding hacking. The resident directly stores their data and is not within the cloud. In this context, cloud storage can be defined by Google as "a mode of computer data storage in which digital data is stored on servers in off-site locations. The servers are maintained by a third-party provider who is responsible for hosting, managing, and securing data stored on its infrastructure" (Google, 2023). Since this data does not leave the safety of the homeowner, there are still disadvantages of not uploading this information to the cloud. For instance, they could damage the storage or use it in an inappropriate manner, like not benefiting from knowing their personal consumption.

- Private cloud is a cloud storage system that is implemented by the company providing smart home services. The organization is the only entity having access to the private cloud as it is responsible for its implementation and maintenance. This model gives the system owner exceptional access control since IT knows where the information is located and can keep an eye on the boundaries that surround the data (Petrova, 2020). Additionally, this storage type is deemed quite secure from hacking. As a homeowner, it is important to be aware of these private cloud storage systems. Whoever oversees the smart home information is accountable for investing in all the necessary material and resources, which could be a high cost for that company. In addition, the organization needs to ensure that they have qualified personnel and expertise to correctly deploy and operate the cloud as it is a complex structure.

- The next type of cloud storage is the public cloud, which is accessible by any user. To properly define this category, we must delineate what 'public' means. According to Petrova, "the term public does not mean that the information of the individual user is publicly available but defines the possibility of using the resources of cloud technology by each registered user" (Petrova, 2020). Public clouds are a cheaper option for companies offering smart home services, but they are more prone to cyberattacks since they depend on a third party. If the public cloud provider were to run into issues or stop offering its services, the smart home company would risk losing data.

- After discussing private and public storage types, we now dive into the fourth category which is a mixture between the two, the hybrid cloud. In practice, it means that a smart home company would store sensitive data (daily routines or personal information) into a private cloud and the rest in a public one. Usually, the hybrid cloud is set up as "a combination of two or more clouds (private, public) that remain distinguishable even though they are connected and working together" (Petrova, 2020). This option allows better maintenance of security level while minimizing costs for smart home companies. It is also an optimal solution for companies which are starting to implement a cloud storage system.

After highlighting the different ways that data can be stored, it would be of interest to know which volumes of data are stored. Unfortunately, as the adoption of smart homes is still ongoing, they have not become a standard practice yet. Therefore, this kind of information is difficult to find. The quantity of data stored also highly depends on the type of data itself. Technologies which use video, such as smart doorbells or security cameras, will require the most storage space due to their heavy nature.

2.3.3 Data Processing

Data collection through sensors is only the first step towards making data actionable. As previously discussed, most of the time smart home information is stored within cloud systems. This means that a smart home service provider is analyzing the data, also known as cloud computing. Today, this is considered as the classical approach. As three authors wrote, ”the conventional wisdom is to offload all workloads from devices to the cloud via wide area networks (WANs) where powerful data centers are located” (Xu et al., 2022). However, this tactic has some disadvantages when dealing with IoT data. For instance, the analytics might be slowed down as data travels from different devices to the cloud and back. In turn, cloud resources are shared between many devices with multiple analyses being performed contemporaneously. If the cloud is experiencing high traffic, this can become a real issue. Furthermore, some smart home appliances require instantaneous results, as it the case with security surveillance systems or some health devices. If the computational responses are not delivered in a timely manner, they become of little use to the end-user. This naturally creates a need for an alternative to cloud computing. A popular solution today is edge computing. Xu et al., 2022 define this concept as ”a distributed architecture that reduces latency by hosting applications and computing resources at locations geographically closer to the data source. Simply put, edge computing alleviates data transferring latency by processing data in local edge nodes rather than in a remote cloud” (Xu et al., 2022). Figure 5 helps to better understand how cloud and edge computing are articulated.

Smart home appliances or services are represented here as End-User Apps. They are ”a source device in a networked system, which generates data by interacting with users (e.g., mobile phones, laptops, etc.) or sensing environments (e.g., cameras, sensors, etc.)” (Xu et al., 2022). In more recent years, End-User Apps can be equipped to perform analytics directly, without the need for data to be communicated to other entities. However, this will depend on the type of analytics required, as more complex or voluminous tasks will require additional computational power.

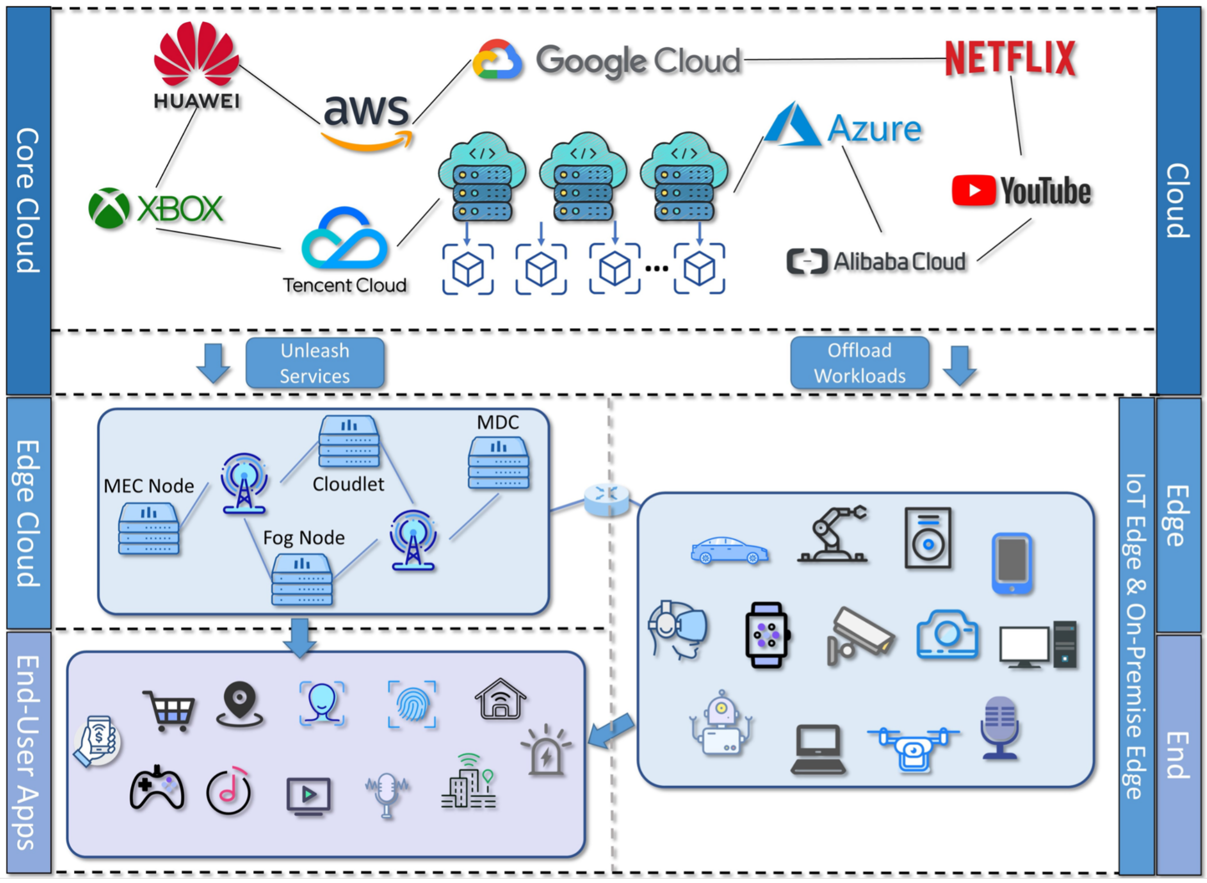

Figure 5: Cloud computing and edge computing architectures (Xu et al., 2022)

In Figure 5, edge computing is divided into three categories: IoT Edge, On-Premise Edge and Edge Cloud. IoT Edge represents ”any device that 1) can communicate with remote entities via local area networks (LANs) or WANs, and 2) has limited computation and storage capabilities to process data locally” (Xu et al., 2022). IoT Edge can represent the same type of products as End-User Apps, but what differentiates them is how they conduct analytics. The same appliance can be both an End-User App and an IoT Edge computational device.

On-Premise Edge corresponds to the idea of a private storage cloud. It is ”intended for private use, and can provide various services to authenticated users (e.g., employees, students) within the LAN, including data processing, data storage, network routing, privacy and security preservation, application hosting, etc.” (Xu et al., 2022). This type of edge computing may be less common with smart homes, but it is still relevant to this topic even though it is oriented more towards private companies or organizations such as universities.

Edge Clouds are usually offered by bigger cloud providers as an extension of their infrastructure deployed on nodes (servers, data centers, etc.) closer to the end user. In other words, Edge Clouds are a way for these providers to extend their infrastructure to the edge of the network, where they can quickly and efficiently process more data. They are particularly used for video media diffusion to fluidify its flow. The top part of Figure 5 depicts Core Clouds, which are akin to public clouds. They are ”remote large-scale data centers with powerful computing capabilities and massive storage space that can provision a large number of scalable and elastic virtual machines” (Xu et al., 2022).

Each of these different layers has its advantages and disadvantages. IoT Edges are the fastest option because they are the closest to data produced by devices, but this advantage must be traded off with their reduced storage capacities and computing powers. They are meant for light and quick data analysis. On-Premise Edges have more consequent infrastructure than IoT Edges, and still have low latency with processing data. Since they are privately maintained, they have the same issues as discussed with private clouds, mainly their increased costs for installation, operation, and maintenance. Edge Clouds inherit the powerful computational aptitudes of Core Clouds and are easy to use, but they are the edge computing layer which is farthest away from the origin of data and thus will have more latency. All these options should not be regarded as competing; rather it is about selecting which one will be more appropriate for that specific task. For instance, deep learning models will require greater resources. Therefore, an Edge Cloud solution would be more appropriate. Easier tasks though can be directly performed by End-User Apps. Either way, a smart home will utilize all these options together and combine them into a fluid system.

3 Smart Home Analytics

3.1 Prediction

One of the challenges in fully realizing the benefits of smart homes is managing the massive volume of data they generate and leveraging it to gain meaningful insights. The vast number of sensors and devices in smart homes that generate real-time information and store historical data make it difficult to draw simple associations. However, machine learning techniques can provide a useful tool for describing and understanding data as well as identifying patterns that can hint at regular human behavior. Various statistical tools are also used to solve a variety of data-related problems. As noted by Mohammadi et al., 2018, ”in recent years, many IoT applications arose in different vertical domains, i.e., health, transportation, smart home, smart city, agriculture, education, etc. The main element of most of these applications is an intelligent learning mechanism for prediction (i.e., regression, classification, etc.), data mining and pattern recognition (i.e., clustering, association, dimension reduction, etc.) or data analytics in general” (Mohammadi et al., 2018). This not only demonstrates that there are many industries being impacted by IoTs and the surge of big data, but that there are applications of statistics being used to realize the value generated by this not-so-new flow of information.

In the context of smart homes, one of the main objectives of this technology is to enable its inhabitants to simplify their lives through predictive technologies. This results in the catering to their needs before or at the time they are required. There are a series of machine learning models that assist in predicting patterns from the information generated by smart home devices or a centralized control center. Tools such as k-nearest neighbors and support vector machines can be utilized among many others, allowing these models to accurately predict “Activity of Daily Living” even when there could be a random or unknown component (Raeiszadeh & Tahayori, 2018).

3.1.1 Supervised and Unsupervised Learning

In the previous section, machine learning algorithms were discussed, outlining how they can be used to gain insights from the volumes of data produced by smart home components. To provide an overview of these mathematical tools, a definition of the two main types of methodologies is presented. Machine learning algorithms can be separated into two groups, supervised and unsupervised methods. The difference between the two can sometimes be complicated, but in essence, it is defined by the amount of human input required. According to IBM, they mention how supervised learning is a type of machine learning technique that relies on labeled datasets to train algorithms in accurately classifying data or predicting outcomes. By providing labeled inputs and outputs, the model can gauge its accuracy and improve its performance through iterative learning (Delua, 2021). On the other hand, unsupervised learning employs machine learning algorithms to cluster and analyze unlabeled datasets, uncovering concealed patterns without human intervention, hence why they are referred to as ”unsupervised” (Delua, 2021).

There are multiple differences between the two learning methods, but the main one stems from labeled data. For instance, in supervised learning, Delua mentioned how “algorithm ‘learns’ from the training dataset by iteratively making predictions on the data and adjusting for the correct answer. While supervised learning models tend to be more accurate than unsupervised learning models, they require upfront human intervention to label the data appropriately” (Delua, 2021). In contrast, “unsupervised learning models work on their own to discover the inherent structure of unlabeled data” (Delua, 2021). By clearly defining the two methods, we can affirm there are important differences that impact the way they are used. Depending on the prediction problem, one method may be superior to the other because the goals, applications, or complexity of said question may be answered more easily with a preferred model to generate refined results. Within the domain of supervised learning models, there are two types of problems: classification and regression. Classification problems are those which have the objective to classify observations into a specific category based on the associated data. Different sensors’ data can be used to classify if a resident or visitor is in a particular room. Models such as linear classifiers, support vector machines, decision trees or a random forest are commonly utilized within this type of problem. For regression though, different algorithms like linear regression, logistic regression and polynomial regression are popular options. This supervised method uses "an algorithm to understand the relationship between dependent and independent variables," typically predicting a variable that is continuous (Delua, 2021). Regarding a smart home application, data on amount of switch triggers and the time they happen could help predict the power consumption of a home based on the consumers behavior.

Unsupervised models are most beneficial for three main tasks: clustering, association, and dimensionality reduction. Clustering is the formation of groups inferred from different data points and potential previously unidentified patterns. This enables us to associate characteristics to the data structures so that knowledge can be created based on the unseen connections within the data. Within a smart home environment, clustering can be used by companies to identify different types of user profiles based on attributes such as power consumption, appliance usage schedules or movement within the house. In addition, association employs various rules to identify connections between variables within a given dataset. The last unsupervised technique is dimensionality reduction, which reduces the number of data inputs to a manageable size while maintaining the integrity of the data. To gain additional insight on these prediction models, a plethora of literature can be found.

There are multiple machine learning algorithms that can be applied to various objectives in the smart home setting. Whether on-site to enable efficiencies at the point of origin or as the end user setting personalized preferences, these statistical mechanisms allow any party to collect more information to improve their understanding of how their home can benefit their lifestyle on a continued basis. As these predictive tools can be acknowledged as inherently valuable, there are also challenges that make prediction or any other kind of application of machine learning rather complicated.

3.1.2 Analytics for IoT Data

Smart home environments face the challenge of how to appropriately process large amounts of data produced by different devices that are connected in the system. As mentioned previously, IoTs generate vast amounts of data that must be considered in any statistical model for it to be worthwhile to predict user behavior. This data differs from simple large data sets (i.e., databases, data lakes) because it has certain attributes that make it more complex. Mohammadi et al., 2018 mention at least four determining differences:

- *Large-Scale Streaming Data*: A myriad of data capturing devices are distributed and deployed for IoT applications and generate streams of data continuously. This leads to a huge volume of continuous data.
- *Heterogeneity*: Various IoT data acquisition technologies gather different information

resulting in data heterogeneity.

- *Time and space correlation*: In most IoT applications, sensor devices are attached to a specific location, and thus have a location and time-stamp for each of the data items.
- *High noise data*: Due to tiny pieces of data in IoT applications, many of such data may be subject to errors and noise during acquisition and transmission.

These data type differences call for specific statistic models, namely streaming analytics. These tools can predict outcomes by appropriately adapting to be reactive and adjusting in real time. While methods for streaming analytics have been developed through cloud infrastructure and services, there is a demand to improve further in the redistribution of these models to less centralized architectures. They need to be flexible and learn well enough to work in the Edge as there is a desire to move computation away from single-point processing to avoid issues with latency. Moreover, streaming analytics for prediction becomes much more important when the type of action being predicted requires very short response time or is not easily predicted due to the multiple components that determine its non-standard behavior.

3.1.3 Challenges: Inconsistent behaviors

There are several diverse techniques that are utilized for prediction problems. However, in addition to the computational difficulties, there exist issues in defining the problem itself. While some patterns can emerge in studying an inhabitant's actions, one of the true drivers of their behavior is their intention which is harder to measure. As mentioned by Choi, "although humans have an inherent ability to understand other people's intention from their actions, it is difficult to extract relationship between actions and intentions in a structured way" (S. Choi et al., 2013). It is this unpredictability that complicates the task of generating appropriate predictions of what a particular individual or household will require and at what time. Regardless, there is some overarching pattern that can be derived from studying the inputs from all devices and sensors. The study by Raeiszadeh and Tahayori, 2018 demonstrates how these machine learning methods can forecast with more than 95% accuracy daily life events like taking a shower, preparing a snack, dressing, or going to work.

There is a wide variety of statistical and probabilistic measures used for the task of anticipating human behavior. Some concentrate on event types like when an action will take place, while others focus on predicting the system as a whole. Both are advantageous in the smart home environment, but their benefit will depend on the prediction problem. As an example, these measures would have to foresee what the next activity would entail (the time) or the place (the location) in which it will happen. The difference of what versus where will also allow for adjusting the selection of predictive tool.

Some intriguing algorithms for smart home behavior predictions are episodes and temporal relations. These two deduct patterns through data about activities and their relationship with time. Regarding episodes, Wu indicates that “the collected raw data does not indicate where periods of device interaction, or episodes, begin and end. The framework searches for the beginning and end of episodes while balancing episode length with frequency and regularity. This approach discovers significant episodes that occur on a recurring basis such as a daily wake-up routine or weekly lawn watering” (Wu et al., 2017). With this algorithm, activities can be anticipated without clearly delimited inputs by users or previous configurations.

Similarly, for temporal relations, a framework was created to allow logical deductions of activities. Their framework is based on 13 temporal relations included in Allen’s temporal logic. Prior to stating those points though, Allen’s temporal logic deals with time and relationship between events. Now, this philosophy should make more sense: “1) before; 2) after; 3) meets; 4) met-by; 5) overlaps; 6) overlapped-by; 7) starts; 8) started-by; 9) finishes; 10) finished-by; 11) during; 12) contains; and 13) equals. This provides additional insight into the timing of events than a stream of symbols which represent individual events which can enhance prediction algorithms. With this information, an algorithm can create predictions with temporal constraints resulting in better detection of anomalies” (Wu et al., 2017).

Smart homes offer numerous benefits, but managing the large amounts of generated data is a significant challenge. Machine learning and statistical tools, such as supervised and unsupervised learning, provide solutions for analyzing and classifying data. These techniques enable predictions and pattern recognition, simplifying residents’ lives through predictive technologies.

3.2 Optimization

Other than the known benefits highlighted throughout this paper thus far about having a smart home system or devices, there is an additional perk of using these smart technologies — optimization of resources. One of the major concerns of new technology implementation is the increased use of electricity for these gadgets. However, the usage of power does not have to increase linearly or even exponentially due to the increase of smart apparatuses. Given the ability to measure different characteristics of smart home users, these technologies can come as an efficiency improvement by reducing the amount, quantity, and duration of power devouring activities in day-to-day life. Therefore, it is possible to optimize energy usage in a smart home environment from sensors and devices where analytics can be performed.

Optimization is one of the most essential aspects in smart home adoption. Having the ability to control and adequately allocate resources when and where they are needed can vastly improve the performance of a smart home in comparison to those who do not use analytical tools. The area where these have the most impact is in the HVAC system. By using environmental parameters such as local season, temperature, and weather forecasts as well as data related to the routines of the inhabitants or personal configuration, smart HVAC systems can efficiently moderate the temperature inside a smart home to adjust to these settings. Therefore, it can optimize the energy consumption to only heat in the required times or stop air-conditioning when no one is home.

There are also many ways to achieve efficiency in a smart home. El-Azab states that ”homeowners may have several criteria to be optimized together. Multi-objective optimization (MOO) problems consider many functions simultaneously. MOO finds a proper coordination that moderately satisfies the considered objectives” (El-Azab, 2021). Additionally, the objective of optimization techniques is to find the most effective coordination while adhering to specific constraints (El-Azab, 2021). In the past decade, classical methods, such as linear programming, were commonly utilized for smart homes with restricted objective functions and basic models for tariffs and home appliances (El-Azab, 2021). However, in recent times, AI-based techniques have been introduced to tackle more intricate models for smart homes, incorporating multi-objective functions and ensuring a comfortable lifestyle (El-Azab, 2021).

Therefore, optimization can provide many areas for improvement based on the smart home system configuration or the personal desires of the smart homeowner. As mentioned previously, multi-objective optimization functions can be applied to these systems. With SHEMS, owners can make the most of these technologies to improve their desired outcome. Several of these objectives are listed in Table 1.

Multi-objective functions of SHEMS

First Objective	Second Objective
Economic-profit maximizing	Emissions minimizing
	Reliability maximizing
Electricity-bills minimizing	Emissions minimizing
	Reliability maximizing
	Lifetime maximizing
	Economic-profit maximizing
Investment-costs minimizing	Emissions minimizing
	Reliability maximizing
	Fuel-consumption minimizing
	Electricity-bills minimizing

Table 1: Source: El-Azab, 2021

As per the table, the primary objectives are usually related to economic optimization, that is reducing initial or ongoing costs or maximizing the profit of the smart home operation. For each of these, additional objectives can be added which can relate to carbon emissions, fuel consumption, reliability or the lifetime of the system. Therefore, smart home systems can provide opportunity for many types of improvements when it comes to home management.

3.2.1 Formal Definition of Optimization

In abstract terms, a problem of optimization consists of three main elements:

- objective function(s)
- variable(s)
- constraint(s)

The objective function is a mathematical expression which describes a goal to be minimized or maximized. For instance, it can be an expression for the total amount of electricity consumed daily in a smart home. An optimization problem can have several objective functions if more than one characteristic is to be optimized simultaneously. The variables are the parameters of the optimization problem which can be acted upon — they are the specifications that the smart home can control. An example would be how the smart home decides which lights to turn on or off, or which temperature to set in each room. In contrast, the outside temperature cannot be a variable, as it is not under control. Changing the variables will impact the objective function: leaving all the lights turned on increases energy consumption. The optimization problem's goal is to find the appropriate values for the variables which give the best result of the objective function. The constraints of the problem are special rules or assignments that the variables must respect. One instance could be turning off the whole heating system to minimize energy consumption. Without giving any constraint to the optimization problem, the solution would result in a shutdown of all heating. However, this is not acceptable if outside temperatures are cold. Thus, adding a condition determining a minimal temperature to be maintained inside the home is an example of constraint which naturally arises in this optimization problem. By utilizing linear programming to find the best possible outcome, the smart home or its devices can make optimal decisions to maximize efficiency to save energy and reduce costs.

3.2.2 Types and Methods for Resolution

Optimization problems can be divided into two main categories: continuous and discrete. This depends on the nature of its variables. Turning a light on or off is an instance of a discrete variable, which is usually called binary. It takes two values, most commonly 1 and 0, which describe the two possible states of the light, on or off. A continuous variable though could be the temperature set in a room. It does not have levels, but rather a possible interval of values to be taken.

Continuous variables usually result in smooth objective functions, resembling curves. This represents an advantage as it is possible to differentiate the objective function, which can be a useful tool for some resolution techniques. However, discrete optimization problems have step objective functions rather than smooth ones. They can be considered as more difficult to solve because differentiation cannot be used in that case. Another aspect which has an impact on the available techniques to solve the problem is whether the problem is deemed convex or not. A convex problem will only have one global minimum or maximum. This makes the resolution easier, and it ensures that the solution is indeed the best possible choice that can be made. If the problem is not convex, then there are multiple local minima or maxima. Depending on the resolution methods used, it is possible to find a solution that is one of the local extrema, but not necessarily the best one. There exist numerous ways of solving optimization problems, and they can be classified as follows. For some problems, there are algorithms which can always find the best solution to the problem. This is the case for simpler optimization problems, such as linear programming. More complicated models might be solved using iterative methods, such as gradient descent. As their name indicates, these techniques are iterative, they attempt to approach a solution step by step, thus converging towards the optimum. Many of these iterative methods compute the derivative of the objective function, which means that they will not be able to solve discrete optimization problems as discussed above. Moreover, iterative methods might converge towards a local extremum instead of the global one if the problem is not convex. Despite these caveats, iterative methods are widely used, when no explicit algorithm for exact resolution exists. They are also very commonly implemented inside predictive models for supervised learning. If no exact algorithm exists or iterative methods would take too much time to find a solution, the ”last resort” option is using heuristics to solve an optimization problem. Heuristic methods do not guarantee that a solution can be found, or that the solution found is the best one. They can also be useful as a preliminary step if the problem is computationally expensive. A heuristic method can help to select potential values or intervals in which the variables give a satisfying solution, and an iterative method can then find the optimal solution only searching in the zones of interest detected using heuristics.

Optimization of resource consumption, in addition to behavior prediction, are two of the main areas of development in the smart home environment. The literature provides multiple studies which apply varying complexity of statistical models and optimization algorithms to propose novel and effective solutions to a multitude of smart home configurations. While the application of these is more a concern for the companies who offer these solutions, there is a large motivation from academia and also the industry, to find improving alternatives as those who more proficiently apply these models can obtain large benefits in aspect of user adoption.

4 Discussion

We have explored two primary uses of smart home technologies, predicting behavior and resource optimization. Now, it is worth mentioning the topics that potentially pose the largest barriers for the adoption of smart home technology. There are multiple factors that come into play when considering these systems or devices, such as how and where they enter a market, who they are intended for and what are they expected outcomes. While some of the issues stem from the fact that technology is still in development, and hence out of consumers' reach. There are economic obstacles such as the cost of implementation but also other more tacit issues such as access to information, the impacts of malfunctions as well as privacy and security of the data collected. Some of these issues will be covered in this section. However, this is not an all-encompassing list, and more information can be found in other literature.

4.1 Cost Analysis of Smart Home Implementation

One of the barriers for adoption is the cost of the technology. Fortunately, the prices set by the manufacturers for these smart home devices have fallen over time as mass-market production increases. Nevertheless, it is still far from access for many consumers. Considering that most customers are from industrialized countries, studies have shown that it is the perception, even in these sectors, that smart home technologies represent a large economic investment and access to these might be restricted to consumer sectors who have more resources (Balta-Ozkan et al., 2013). Mostly family-oriented homes and new constructions appear to be the target group for these technologies. Unfavorably, older homes may see issues in adopting these technologies as home adaptation to them might represent a larger upfront investment than new constructions. Additionally, families with multiple income sources are more likely to invest rather than young professionals as the margin available resources for the transition is larger in the former. (Balta-Ozkan et al., 2013)

Balta-Ozkan et al., 2013 indicates that "[consumer] groups viewed smart home services as for homeowners who were settled in the same property for a number of years. This excluded them as renters, and smart technology was also seen as out of the reach of first-time buyers who would struggle to afford smart home services. Within this context, it is unsurprising to find that younger participants saw smart home technology as a luxury". Therefore, cost is not only analyzed from an initial cost point of view but includes other expenses such as maintenance and the actual return on investment this would equate to. "Regarding potential cost savings, [consumers] would want to see substantial savings for it to be worthwhile: saving 'a few pence' would be meaningless. There was speculation that smart home technology would leave people 'constantly worrying' and feeling guilty. Running appliances when electricity is cheaper was often perceived as pointless if savings were minimal, as well as requiring inconvenient changes to household routines" (Balta-Ozkan et al., 2013). Hence, it is perceived that consumers are very cautious of the financial impact that such technologies would have regarding their implementation. Overall, cost is seen as one of the most important problems smart technologies have for widespread adoption.

Evidently, the total expense is directly linked to the number of technologies and devices used in one's home, and the extent of the activities that are automated. Though there is little academic work on standardized, equivalent, and updated data on the cost of different levels of implementation of smart home technologies and gadgets, various home improvement magazines and companies share a high-level approximation of the average costs. Information on the Toronto, CA market indicates mean cost of $350 to $500 per square feet. Table 2 can provide a general idea of the costs associated with purchasing and installing smart home technologies.

Part of the House	Average Cost (in CAD)
Total Home	$20'000
Kitchen	$9'000 - $25'000
Bathroom	$2'000 - $25'000
Climate Control	$750 - $2500

Table 2: Source: Own creation with data from Smart Home Features Guide (Cumming, 2022)

As per the table, it is possible to see that the range of costs can change significantly depending on the type of installation of devices used. Additionally, publications from Buildit Magazine in the United Kingdom show a range from £15'000 to £150'000 depending on the quality and number of devices, size of the home, and level of integration (Brooks, 2022). Not only is cost a question when considering entering the smart home device market, but there are additional limitations about who is actively interested in these technologies. Various literature has been able to identify a few groups such as "—elderly or vulnerable householders, rational energy users, technophiles, home improvers and differentiated families" (Wilson et al., 2014). The reasons behind why these groups are particularly interested in this technology differs, from assisted living via "accessible contact with emergency help, assistance with hearing or visual impairments and automatic systems to detect and prevent falls" to more comfortable and automated "ICT-enhanced lifestyles" (Wilson et al., 2014). Nevertheless, it is a known characteristic that these groups are somewhat clearly identified, and that the broader adoption of these devices is an active problem for industry.

4.2 Ease of Use, Reliability, and Compatibility

There is one issue related to the attribute of ease-of-use. If the technology itself is costly, but also complicated to install, use, or maintain, the consumer will be hesitant to even consider purchasing it. As mentioned previously, if the consumer sees technology as a roadblock, then its overall benefit will be reduced. Moreover, this introduces the issue of reliability. Currently, house security is ensured by locks on gates, doors, or windows, and can be manually set and reset. Nevertheless, there are trust issues with regards to what happens if a homeowners' system malfunctions. Perceived notions of loss of control of the objects securing the home are also top of mind when it comes to barriers of adoption. The idea of getting locked in or out of your home is not a worry anyone wants when they decided to implement smart security systems.

While most smart devices continue to support manual override, the potential loss of control is still largely impactful for some consumers.

Another barrier to adoption comes around network and device compatibility. As the industry is rather young, there are multiple methods, processes, and standards used by different companies. Each corporation may decide to use certain rules for communicating between the devices they produce but may differ amongst competitors. This introduces a complicated issue for the consumer who might have to either faithfully buy every device offered by a single company or risk having useless units from different companies that do not work seamlessly together. Petrova, 2020 stated that "it is known that there are very few globally accepted industry standards applicable to smart home systems. This creates problems for homeowners who want to automate their homes. Without industry standardization, it is possible for someone to invest in an entire system that will not communicate adequately with all devices". While there have been efforts in the market to reduce the number of different protocols, this does not mean consumers should not be aware of what they are purchasing. Additionally, as mentioned by Lin and Bergmann, 2016, "system heterogeneity is a vulnerability. Devices come from many manufacturers, with different networking standards and different software update capabilities. Often the devices have little or no documentation about their internal software, operating systems, and installed security mechanisms". Not only is the variety of protocols and standards an issue for the consumer in the sense that not all devices might be compatible, but this lack of information on how they communicate with each other could also become a security risk.

4.3 Security Risks in Smart Home Environments

Security can be considered as a trade-off. While one consumer finds this to be beneficial to their home, others deem it has a potential threat. Being disconnected from smart devices and the internet means there are less ways to access valuable knowledge that could put someone in danger. Those that have not jumped on the trend to implement smart devices in their homes have done so with purpose. They do not want their data to be accessible from outside forces, which could give them control over the residents' home and them. This is one main reason why security and privacy are one of the major concerns for users. As Wilson has outlined, "the acceptability of smart homes to users is closely linked to issues of security, privacy and trust as well as practical and ergonomic concerns with user-friendliness. These issues present critical design challenges that relate to the interactions between users and smart home technologies" (Wilson et al., 2014). Consumers expect smart technologies to be trustworthy, not only in terms of avoiding malfunctions but also in terms of protecting their privacy. As a result, they demand that companies collecting their data use available security tools to safeguard their information.

Balta-Ozkan et al., 2013 noted that smart homes collect data on inhabitants' activities such as movement, energy use, purchases, and preferences to tailor the system to their lifestyle. The industry must ensure that personal data is protected while providing remote control of security services to prevent compromise of sensitive systems. If this combination of practicality and profound security cannot be met, it is unlikely that smart home technologies will ever reach a mass-market as they introduce new risks to home ownership. If implementation of these devices makes the end-users feel unsafe or controlled, they will most likely revert to non-smart homes to ensure their security and privacy is not being compromised.

There have been studies performed to understand the level of risk and the potential problems faced with smart home infrastructure both by itself and with its relation to smart grids. Komninos et al., 2014 highlight some of the major attributes of security:

1. **Confidentiality**: The assurance that data will be disclosed only to authorized individuals or systems.
2. **Integrity**: The assurance that the accuracy and consistency of data will be maintained. No unauthorized modifications, destruction or losses of data will go undetected.
3. **Availability**: The assurance that any network resource (data/bandwidth/equipment) will always be available for any authorized entity. Such resources are also protected against any incident that threatens their availability.
4. **Authenticity**: The validation that communicating parties are who they claim they are, and that messages supposedly sent by them are indeed sent by them.
5. **Authorization**: The assurance that the access rights of every entity in the system are defined for the purposes of access control.
6. **Non repudiation**: The assurance that undeniable proof will exist to verify the truthfulness of any claim of an entity. (Komninos et al., 2014)

There are certain attacks on smart homes that can considered as passive and active. The first type relates to activities that do not necessarily affect the system or the data flow of the smart home but continue extracting necessary information to obtain some gain. Two examples of this attack would be eavesdropping or traffic analysis. Eavesdropping intercepts data flowing in and out of the system network, keeping it for the use of the attacker. Traffic analysis does not look at the data but observes the flow and makes inferences on behaviors based on this flow. As these do not interfere with the network itself, they are very hard to detect. The second type of attack is active, which has a clear and identifiable impact on the system or even the devices of the smart home. One example includes masquerading, where the attackers impersonate a legitimate entity to obtain privileges. Another attack can involve the interception and delay of message transmissions by and to the system or even a denial of service which can ”temporarily or permanently suspend the availability of the communication resources of a system” (Komninos et al., 2014).

Scenario num:	Possible Threats	Security Goals Compromised	Degree of Impact
SH_1	Eavesdropping (N) Traffic Analysis (N) Message Modification (N) Replay Attack (N) EMS Impersonation (SH)	Confidentiality Integrity Authenticity	Low-Medium
SH_2	Repudiation (N) Message Modification (N) Replay Attack (N)	Non repudiation Integrity Authentication	Medium
SH_3	Tampering/Reversal/Removal of Meter (SH) Illegal Software Modification/Update (SH)	Authentication Integrity	Low
SH_4	Customer Impersonation (N) Device Impersonation (SH) Message Modification (N) Replay Attack (N) Repudiation (N)	Integrity Non Repudiation Authentication	Low- High
SH_5	Customer Impersonation (N) Eavesdropping/Message (N) Interception (N) Message Modification (N)	Confidentiality Integrity Authenticity	Low-Medium

Table 3: Source: Komninos et al., 2014

After having identified these invasions, the authors have also mapped potential breaches and their severity to the corresponding security attribute they affect. Table 3 contains information about different activities, both passive and active, which have been charted to different smart home scenarios. For this report, we will only consider the types of breaches and their effects. As we can see from the Table 3, there are several risks with varying degrees of impact to a smart home system. Some possible threats are also non-exclusive of security gaol. Eavesdropping and Message modification can affect in multiple areas also with different impact levels. Despite this, some users are still willing to employ the technology knowing what risks they imply. All these issues need to be addressed by smart technologies companies to ensure they are properly considered and managed.

4.4 Trends and Recommendations

Since the 20th century, domestic technology has advanced in unimageable ways. From electricity entering homes to refrigerators telling the owner they are low on milk, society has benefited from incorporating these nifty gadgets into their households in numerous ways. Today, people expect to see a wide variety of devices when it comes to smart home IoTs and the building itself.

According to Forbes Home, there are several trends that home-buyers seek when in the current and future market. The most important one appears to be integration because people expect that their new home will come connected and have the ease-of-use functionality where various devices communicate with one another to meet an objective (Meredith Hirt, 2023). People also are wishing to incorporate artificial intelligence, like Amazon Alexa, which has shown its continuous improvement to understand commands and respond in different manners that make life in a smart kitchen or bathroom more enjoyable (Meredith Hirt, 2023). Additionally, the third most prevalent trend is installing ”touchless tech” (Meredith Hirt, 2023). The Ring doorbell was mentioned earlier, and this was just one example that homeowners or renters could add to their list of smart devices to help with potential security threats. As most of these gadgets are reasonably affordable, they have the potential to become cheaper with additional research and technological advancements. For instance, one author described a trend where a smart home system is presented by ”a simple, low cost, flexible and multi-purpose remotely controlling and monitoring system based on a smart phone with a sophisticated wireless communication medium (Wi-Fi)” (Waleed et al., 2018). As this was written about five years ago, consumers are now experiencing this as smarter home technologies become widely accessible making it easier to connect through mobile devices by Wi-Fi or Bluetooth. Another interesting movement has been in literature. One report reviewed publication trends from 2015 to 2019, and they noticed that the ”percentage of smart home IoT (SHIoT) articles in the IoT domain remained constant, but that of SHIoT articles in the smart home domain significantly increased from 2015 (18.43%) to 2019 (43.70%)” (W. Choi et al., 2021). This means ”that the number of articles concerning smart homes remained constant, whereas the number of articles covering SHIoT research increased between those four years by more than 4.5 times. The social and industrial effects of smart home and IoT domains are increasingly becoming important”, and this continues to be seen throughout reports (W. Choi et al., 2021).

This paper has extensively covered smart homes, but there is one additional section that we would be remised if not mentioned. There are several recommendations that could possibly be important for the future research conducted in the smart home industry. One of the main disadvantages of smart home technologies is the threat of intruders or hackers into a consumer’s device(s) or network. Therefore, it is suggested that implementing enhancements for privacy and security is a necessity (Zaidan & Bahaa, 2020). As the data collection and analytics behind these smart home appliances advance, researchers should focus on recognizing how to improve efficiency and energy management with a combination of AI methods. Such algorithms could include K-pattern clustering or neural networks to accurately predict through the sensitivity of sensors when these appliances should be functioning (Zaidan & Bahaa, 2020). Furthermore, additional ”work related to the IoT application, the inclusion of other factors or attributes that may affect the research outcome are recommended in the research on consumer behavior modification and the improvement of smart home systems as these factors influence consumer behaviors in energy usage, such as social, cultural and behavioral factors, should be expanded” (Zaidan & Bahaa, 2020). This is not an exhaustive list, but these three proposals are ways to improve these domestic technologies to ensure that the analytical and technical objectives are satisfied, while meeting consumers’ needs.

5 Conclusion

Smart homes represent a wide range of technologies which have continued to evolve in the last decades. As the general field of artificial intelligence is flourishing more rapidly, smart homes are expected to follow this trend too. However, their expansion is not without concerns. Most of the recent technological innovations have shown themselves to be progressing faster than their corresponding safeguards and regulations. As smart homes become more widespread and their adoption progresses, issues mentioned in the previous section about their safety will need to be confronted. For instance, the European Union is currently discussing an Artificial Intelligence Act which should be implemented within the year (Feingold, 2023). This type of legislation, coming from an important political actor, could have profound impacts on smart home technologies not only in the EU but around the world, improving their overall security and decreasing data privacy concerns.

As the smart home market is still young, there has not been a company which has established itself as the predominant reference yet. Big tech companies have developed diverse smart home technologies, such as Amazon Alexa or Google Nest, but there is no market leader yet, especially when considering the purchase of a smart home as a total system instead of the addition of smart appliances acquired separately (FortuneBusinessInsights, 2022). The apparition of one global leader which would offer turnkey smart homes can also be challenged. Indeed, managing the total implementation of a smart home requires extremely diversified areas of expertise, ranging from data science to civil engineering as it is a very complex process. As climate change becomes a pressing and essential issue, smart home technologies regarding reduction and optimization of energy consumption could be one of the essential axes of smart home development. The energy crisis during winter 2022 caused by the war between Russia and Ukraine increased the interest for smart radiator thermostats in Switzerland (Clémence et al., 2023). However, as smart home technologies themselves consume electricity, they will have to be effective for the energy reductions they bring to be significantly greater than their own consumption.

In conclusion, smart homes are a vast and diverse field of new technologies which are full of potential. As with all technologies, sizing and apprehending them is a complex task, and smart homes are still very juvenile for their long-term impact to be determined. It is good in this context to be reminded of Kranzberg's first law of technology: "Technology is neither good nor bad; nor is it neutral." (Kranzberg, 1986). What Kranzberg wanted to express when establishing this essential rule is that "technology's interaction with the social ecology is such that technical developments frequently have environmental, social, and human consequences that go far beyond the immediate purposes of the technical devices and practices themselves, and technology can have quite different results when introduced into different contexts or under different circumstances" (Kranzberg, 1986). Smart homes are no exception to this rule, it will be essential to keep an attentive eye on them in the future and examine them under a multidisciplinary prism.

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