UiT The Arctic University of Norway

Faculty of Science and Technology
Department of Computer Science

Personalized Nudges with Edge Computing

Data collection and processing with Edge Computing in a Smart Nudging System

Elisabeth Sie Andersen

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To Doris.

"You must use your little grey cells mon ami"
–Hercule Poirot

"To start something is good, but to finish it is a miracle."
–Richard Strawbridge

"If you believe in yourself, with a tiny pinch of magic all your dreams can come true!"
–SpongeBob

Abstract

This thesis aims to investigate the role of edge computing in a smart nudging system. A smart nudging system has requirements for efficient data processing of personal and context-aware data from heterogeneous sources. Furthermore, a smart nudging system needs to protect and preserve the privacy of data within the system. Edge computing has been proposed as a computing paradigm in a smart nudging system to accommodate some of these requirements. The edge computing paradigm makes promises of low latency, context-aware data collection and contributions to privacy when running on an edge device. However, edge computing has limitations in resources for heavy computations and storage. Therefore, a smart nudging system, NuEdge, has been proposed to utilize edge computing resources integrated with cloud computing, a local server, and IoT devices for better performance, privacy storage, and data off-loading. Further, a prototype of the NuEdge system has been implemented to discover the possibilities and limitations of the prototype in a real-world scenario. The primary nudge goal of the system is to improve physical activity for inactive users. By gathering research on edge computing and smart nudging, combined with the implementation's observations, has edge computing's role in smart nudging been evaluated. Edge computing has significantly contributed to efficient data collection in a smart nudging system and lower latency for data transmissions. Future work should include a large-scale prototype and new technologies like 5G to investigate the limitations of edge device capabilities such as power consumption, storage, and computational power.

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Introduction

A nudge is any attempt to influence a person towards a specific option without limiting their freedom of choice. With knowledge about the person and their choice architecture (i.e., the environment in which a user makes decisions) are nudges constructed to guide users towards a beneficial decision for both society and the user. For example, suggesting hiking routes may motivate users to partake in more physical activities, improving their physical well-being, and saving society from lifestyle issues such as obesity.

The term nudge was introduced in 2008 by Thaler and Sunstein[1], who provided the following definition:

> "*...any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives[1].*"

Nudging differs from other choice architectures by not allowing the use of significant economic incentives or the removal of options, as it may be considered unethical. For example, a nudge can not be paying someone to go to the gym as it is an economic incentive, but it can be providing information about aerobics classes at the gym to motivate and influence behavioral change. Thaler and Sunstein aim to increase the probability of good decision-making by ethically nudging users, resulting in more well-being in society.

The concept of nudging has further evolved to utilize digital tools and resources to construct and evaluate nudges. Nudging happening within a digital choice environment is called digital nudging[2]. With the help of technology, the nudging process can become more efficient in automating, customizing, and processing data faster than humans. For example it is more efficient to have a step counter detecting steps then a human writing it down as the user walks. In addition, a digital device can be wearable and, thus, more convenient than a human having to follow a user around to register their steps.

Furthermore, smart nudging is the idea of tailoring nudges to specific users to make them more perceptible for nudges. Personalization and context-awareness applied to nudges are predicted to increase the number of successful nudges[3]. In addition, research on persuasive systems suggests that users show social responses from interacting with computer systems similar to those seen when interacting with humans. Therefore, computers are able to influence and motivate users, as a persuasive host[4].

Constructing successful nudges, in order to create behavioral change, requires efficient data collection and processing. In addition, tailored nudges rely on personal and context-aware data, requiring data protection and privacy. A system for smart nudging has been proposed by Karlsen and Andersen[3]. However, an implementation or detailed system design remains to be created.

1.1 Motivation

Decision-making is an issue every human is faced with multiple times a day. In order to make a good choice we need information to assess the different advantages and disadvantages of the available options. However, as humans, we have a limited capacity to process information, we are irrational, and we have biases[5]. Therefore, humans would benefit from assistance in the decision-making process. Nudging is a way to create behavioral change by influencing the user's decision-making process.

Physical health is one domain that could benefit significantly from changing behaviors, both for the individuals and for society. Common health issues like smoking, little physical activity, and obesity are lifestyle issues. These health issues are easily diagnosed, but treatment relies on the participation of the patient and their efforts. Compared to the need for surgery when treating a broken foot or arm, smoking or weight problems can be treated through behavioral change. With digital nudging, patients can treat themselves without intervention from a physician or doctor. In addition, the nudging can decrease financial expenses both for the patient and society. Self-treatment reduces expected costs, such as the cost of consultations, surgery, medications, and other medical expenses associated with common lifestyle issues.

Digital nudging takes advantage of the emerging digitalization and vast amount of data generated from users as we go from consumers to co-producers. Cisco Visual Internet report[6] registered and predicted an increase in users with internet access and the amount of smart devices. By collecting information and data from multiple sources such as bus tables, fitness gym opening hours, step counters etc., can we create personalized nudges.

Using personal and user-specific data collection, targeting nudges may help influence people's choices. Smart nudging proposes more efficient nudges[3], where personal data is collected to improve and affect users in different domains.

1.2 Problem Definition

A smart nudging system has specific requirements in order to nudge users successfully. Mainly, such a system is dependent on collecting personal and context-aware data to tailor nudges to particular users in a timely manner. With the vast amount of digital data available, the smart nudging system's job is to collect, process, and analyze this data to create relevant nudges, which will motivate users to make better choices. In addition, smart nudges should be processed efficiently to deliver nudges on time. For example, bus table data is only relevant before a bus has departed the user's bus stop. Consequently, a smart nudging system's main challenges are efficient processing, data collection and storage.

Edge computing is a paradigm that focuses on utilizing edge device resources at the network edge for data processing[7]. An edge device, such as smartphones, sensors, cameras, watches, may process data closer to the origin of that data, taking advantage of the proximity. Edge computing promises lower latency, supports privacy, and can gather and collect personal and context-aware data close to the user. These benefits may assist in achieving efficient data collection and processing in a smart nudging system.

Therefore, by combining practical software development and research of nudging and behavioral change, this thesis aims to answer the following research question:

What role may edge computing have in a smart nudging system?

The thesis will evaluate the contributions edge computing can have in a smart nudging system, and present an implementation of a smart nudging system utilizing edge resources. In addition, discussion about benefits and challenges should contribute to determining the potential role of edge computing in a smart nudging system.

With the research question in mind, will a smart nudging system applying edge computing practices be implemented. The smart nudging system prototype will evaluate the usefulness of a smart nudging system in a real-world scenario; to improve physical activity. Furthermore, comparing edge computing with other technologies and components, including cloud and IoT, will present alternative approaches and techniques used in smart nudging.

1.3 Goals

The main goal of this master thesis is to evaluate the role of edge computing in a smart nudging system, especially regarding data collection and processing. The goal is to determine if and how edge computing may benefit a smart nudging system. By comparing edge computing to other alternatives, the thesis would provide insight into the variety of technologies and approaches and how edge computing differs.

The goal of the implementation is a proof of concept to demonstrate the use of edge computing in a smart nudging system. The implementation will give insight into a possible use case of edge computing and identify the challenges and benefits of the system.

1.4 Approach

Firstly, the thesis will look at existing research to identify concepts in edge computing and the smart nudge system regarding data collection and processing. Information about nudging will help determine the possibilities and limitations of a nudging design and system. Research on edge computing can lay the premises for what the paradigm offers compared to a classical computing paradigm and how to utilize edge devices.

Secondly, a prototype for a smart nudging system focusing on efficient data collection and processing will be implemented. The prototype should implement a smart nudging system utilizing edge resources. The smart nudging system will nudge users based on collected data from the edge device.

Thirdly, the prototype and the research provide the groundwork for an evaluation of edge computing in smart nudging. This analytical study will evaluate the physical prototype, the design of a smart nudging system and the role of edge computing in smart nudging. The thesis aims to be a reference for future work to be done on the topic of edge computing and smart nudging.

1.5 Assumptions and Limitations

The Smart Nudge System[3] outlines the whole system, from the gathering of a user profile to the generating and adapting of nudges. Due to time constraints and the size of such a system, this thesis is focused on the challenges of efficient data collection and processing. The prototype will focus on replicating the functionality of a smart nudging system while residing on an edge device.

A major issue of any system is the protection of personal data. Edge computing contributes to privacy by storing data locally. However, it would generally need to implement additional security mechanisms. Security of data is of great concern to users, but this thesis is limited to discussing the general privacy achieved through data placement. The thesis will discuss privacy but without focusing on incorporating security mechanisms.

1.6 Methodology

This thesis explores the contributions edge computing may have in a smart nudging system using qualitative research methods. The research is focused on creating theories about the subject of edge computing in a particular environment, a smart nudging system.

The applied research method is used to investigate the challenges and possibilities of edge computing based on previous research and data. Further, is the inductive research approach used to formulate arguments for design choices of a smart nudging system based on applied research discoveries.

The deployment of a system prototype is conducted as a case study. The study observes the impact an edge-based smart nudging system has in a specific environment and scenario. The observations from the prototype and research contribute to evaluating edge computing's role in smart nudging.

1.7 Contributions

The main contribution of this thesis is to research the possibilities for edge computing in a smart nudging system. More specific contributions include:

- List of requirements for a successful smart nudging system and the role edge computing play to accommodate these requirements.
- A discussion of the possibilities and limitations of edge computing in smart nudging.
- Proposed system design, called NuEdge, for a smart nudging system integrating an edge device, cloud, local server and IoT device. Includes a discussion on categorization of data to help determine storage location in the NuEdge system. Data categorization gives insight to how and where data processing and storage should happen.
- Prototype of a smart nudging system utilizing edge device resources together with IoT and cloud. The system provides an implementation of a smart nudging system and demonstrate different approaches for data collection and integration.

1.8 Context

This thesis is conducted under the Open Distributed Systems (ODS)[1] group and their NUDGE project at The Arctic University of Tromsø (UiT). The goal of the group is to construct and research middleware, mainly in regards to interoperability and adaptability. This also include, but is not limited to, applied security, collaborative editing, composition-based web applications and personalization. As for the NUDGE project, the aim is to change peoples' behavior through the use of nudges constructed with digital data collection and analysis.

1.9 Outline

The outline for this thesis is as follows:

Chapter 2 - Technical Background
Chapter 2 introduces relevant concepts and technologies, as well as explain the

1. https://site.uit.no/ods/

theory of nudging, different types of nudges and techniques. Furthermore, it presents edge computing and different edge techniques, cloud computing, IoT and smart devices.

Chapter 3 - Related Work
Chapter 3 presents related work on nudging and edge computing. Additionally, related work on recommender systems and monitoring systems with edge computing is presented.

Chapter 4 - Method and Methodologies
Chapter 4 describes the scientific methods used for this thesis and how the research has been conducted.

Chapter 5 - Edge computing in Smart Nudging
Chapter 5 explains why edge computing can be relevant in regards to nudging and the approach for designing the NuEdge system. Cloud and IoT is introduced as complementary technologies to accommodate challenges of edge computing in a smart nudging system.

Chapter 6 - Design of the NuEdge System
Chapter 6 presents and describes the design of the NuEdge system, including the proposed system architecture, an integration setup and a presentation of design choices.

Chapter 7 - Implementation
Chapter 7 describes the system overview of the implementation, and presents the experimental setup and used technologies and techniques.

Chapter 8 - Evaluation
Chapter 8 evaluates the conducted research on edge computing and nudging, the NuEdge design system, and observations from the implementation.

Chapter 9 - Conclusion
Chapter 9 presents a conclusion for this thesis.

2

Theoretical Background

This chapter presents relevant concepts to be used as research in this thesis. It also includes presentations of available technologies that might not be part of the implementation, but which illustrates the variety of alternative technologies. Each section aim to present the goal of the technology, as well as the benefits and challenges.

Firstly, in section 2.1 the general concept of nudging is presented by exploring the different kinds of nudging, ethics and the smart nudge system. Section 2.2 introduces edge computing. The section presents the concepts involving edge computing, and explains edge computing technologies such as fog, MEC and Cloudlet in order to provide an insight into exisiting technologies. Further sections introduce cloud and IoT as concepts that can benefit edge computing. Section 2.3 presents cloud computing, different kinds of clouds and deployment models. Lastly, section 2.4 introduces IoT and smart devices. A definition for smart devices is presented, and sensors in smartphones are introduced as this is a common device and a tool in the IoT world.

2.1 Nudging

A nudge can be any attempt to steer a person towards a desired decision without removing their freedom of choice. Nudges aim to use knowledge to help users make decisions that benefit the decision-maker without limiting their options.

Decision-making is big part of everyday life for a person, as we have to deal with different options and decisions on a daily basis. Often decisions can be time consuming, and a lot of research has been conducted to try and predict the outcome of decisions[8]. Previous theories in decision-making have suggested that people making decisions are completely informed, infinitely sensitive and rational[8]. Newer research does no longer support these assumptions as people have shown neither of these attributes, but rather recognize that people's decisions are influenced by the presentation of the problem as well as the norms, habits and personality of the decision maker[9]. The structure of information that goes towards making a decision is known as a choice architecture[1]. The way a choice is presented is never neutral and the options of design often affects the user unintentionally[1]. By intentionally structuring choices and designing nudges within a choice architecture, can we influence the user in their decision-making.

The theory of nudging tries to explain how to create incentives that increase the probability of a person making the choice that is most beneficial to both the user and society. An example of a nudge can be to put fruits closer to the checkout counter in a supermarket. This can encourage healthy meal choices for the user, which can lead to an increase in well-being as well as decrease the risk of lifestyle diseases such as diabetes or heart disease, which benefits society.

In general can a nudge be defined as:

> "*...any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives[1].*"

The definition belongs to Thaler and Sunstein, who helped define the importance of nudging as part of Libertarian Paternalism[1]. Libertarian Paternalism provides the user freedom of choice while nudging them towards the desired choice, as humans are irrational beings[1] and sometimes need guidance. They proposed that nudging can influence people's choices but emphasized that all options should be available to the user in the moment of decision-making. Nudges do not choose for the user but instead aim to use knowledge to help the user make a choice. For instance, a nudge can use last month's takeaway expenses to raise awareness around dinner choices or savings. Freedom of choice sets nudging apart from other choice architectures, such as recommender systems, where options are limited to steer the user towards a specific option.

Recommender systems on the other hand, use software to provide the mostly likely suggestion to a given user[10]. In a recommender system the goal is to identify an item as most desirable, referring to a specific item such as a book or TV-show, and to make a recommendation so that the user chooses this item. The recommendation is based on the interests of the user and on previous preferences. Recommender systems aims to predict user preferences by using different techniques to filter out options, such techniques are collaborative filtering, demographic filtering and content-based filtering[11].

Similar to RS, does nudging aim to make some options more appealing through the use of different techniques. Table 2.1 shows some known techniques and their implementation. These techniques have shown results, in scientific experiments, in directing users towards a specific choice[3, 12]. Although the techniques have shown to have an impact on the decision-making, the effectiveness of such techniques depends on the targeted user and the availability of incoming information.

Technique	**Implementation**
Default	A default choice is presented automatically. **Example:** Previous amount of donation is selected when making a new donation. Insurance is selected when buying a new car.
Simplification	Reduce complexity, by making the choices easy to navigate and pick. **Example:** Displaying less information in a form and adding a question mark button for when further explanation is needed.
Reminders	Sending out a message to remind people. **Example:**Getting a text message a day before your dentist appointment.
Warnings	Attention triggering graphics and text to warn the user. **Example:**Displeasing pictures on cigarette packets to show the affect of smoking.
Past choices	Information about past choices can predict future consequences based on those choices. **Example:** Show a user the money spent on coca-cola last month in their online bank account.
Social norms	Inform about what the general public think or do. **Example:** Message about how 90 percent of people in Ireland believe that people should pay their taxes on time[12].

Table 2.1: Nudging Techniques.

2.1.1 Digital Nudging

Digital nudging is the use of nudging to guide decision-making in digital choice environments. There is an increase in digitalization of both our professional and private lives, with the increase of smart devices and growth of new technologies[2, 6]. Digitalization is increasingly becoming common in domains such as social media, online business, health services, e-learning, finance and insurance, security and privacy and E-government[2]. Tons of choices, which previously was made offline through human interaction or writing on paper, are now made online. These new online choice environments comes with new ways to influence users by user interface design and workflows[2].

Digital nudging differs from nudging by the use of digital data and tools to construct and evaluate a nudge within a digital choice environment[2]. An example of a digital nudge is notifications giving feedback on bus tables, suggesting using public transportation instead of driving to work. Digital data is collected, processed and analysed using technology to digitally nudge the user.

With the internet and mobile devices advancing, the amount of time spent online has increased and the proximity to users has decreased[13]. The internet and mobile devices offers benefits, such as information sharing, by combining personal data produced by the user on a mobile device with mass communication and media from other users on the internet[13]. Information sharing provides more data to perform comprehensive analysis of the user and nudges compared to non-digital nudging. Digital nudging benefits from the large amount of digital data, closeness to the user and the processing power of computers to construct digital nudges compared to normal nudges.

Common challenges when working with digital nudges revolve around the collection and processing of digital data, such as data processing, privacy and security. Efficient data processing is essential to deliver nudges that are relevant in terms of content and time, but this demands processing resources and storage. The life-span of certain data is limited and might only be relevant for a couple of seconds, therefore, demanding high processing power. Furthermore, there is the need for secure storage of collected data. With everything being digital and stored on devices connected through a network, the data becomes vulnerable to misuse during the time of transfer and storage. Privacy is of great concern to users, and their digital data needs to be protected against hackers trying to take advantage of their data. Creating systems that preserve and protect data is one of the main challenges with digital nudging.

2.1.2 Smart Nudging

Smart nudging is the idea of nudges being tailored to a user through personalization and context-awareness, and hence making the user more perceptible to nudging[3]. Karlsen and Andersen[3] introduced the idea of smart nudging; a more personalized nudge based of the information of the user, compared to general nudging. Earlier research on computer systems and interaction with users, supports the idea that adapting a computer system to respond to a certain personality type increases the user's preferred engagement with the computer system[4]. Additionally, research which was part of the Stanford similarity studies, further claimed that people working with computers they perceived as similar in personality, was reporting the system to be more competent, satisfy to work with and beneficial[4].

Smart nudging is an extension of digital nudging, but with more focus on each individual user in their environment. The challenges of digital nudging, such as efficient data processing and protection of data, are also present in smart nudging. With the added personalization and user specific data collection, privacy becomes even more important in smart nudging than digital nudging. Smart nudging, by having a user profile which connects an individual in the world to multiple data, can cause more damage in the wrong hands. For example, might data about a user's travel interests; which bus you take and when, provide an insight into their work location or when they are out of the house. The same personal data used to improve a smart nudge, now also becomes an issue of privacy.

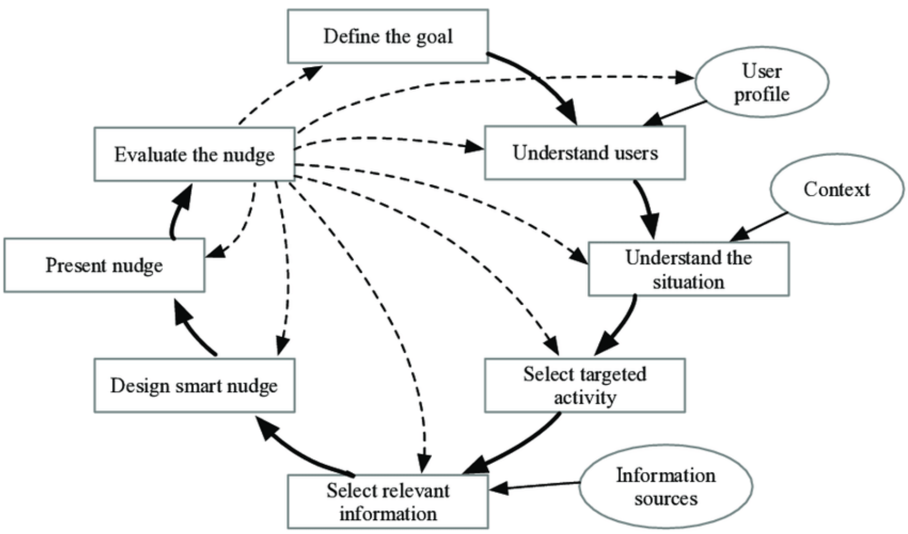

Figure 2.1: Designing a smart nudge[3].

Karlsen and Andersen further proposed a smart nudging system and introduced the general steps to construct a smart nudge in Figure 2.1 and the architecture of a smart nudging system in Figure 2.2. The important steps in designing a smart nudge is to focus on a main nudging goal, which should reflect a goal for the greater good that can be achieved through nudging[3]. The next step will be to understand the user and the environment in which the nudge is to work, and then select a fitting activity to nudge. When a fitted activity is chosen can one start to gather information from multiple sources and design the nudge. Lastly, nudging the user by using the gathered information to help present the nudge in a fitted way for a specific user. The smart nudging system architecture and components are explained in section 2.1.4.

2.1.3 The Smart Nudging System

The smart nudging system is a proposed architecture from Karlsen and Andersen[3], on how to implement a system to accommodate personalized data collection and nudge design. The system depicted in Figure 2.2 consists of four main components and activities needed for the creation of a smart nudge.

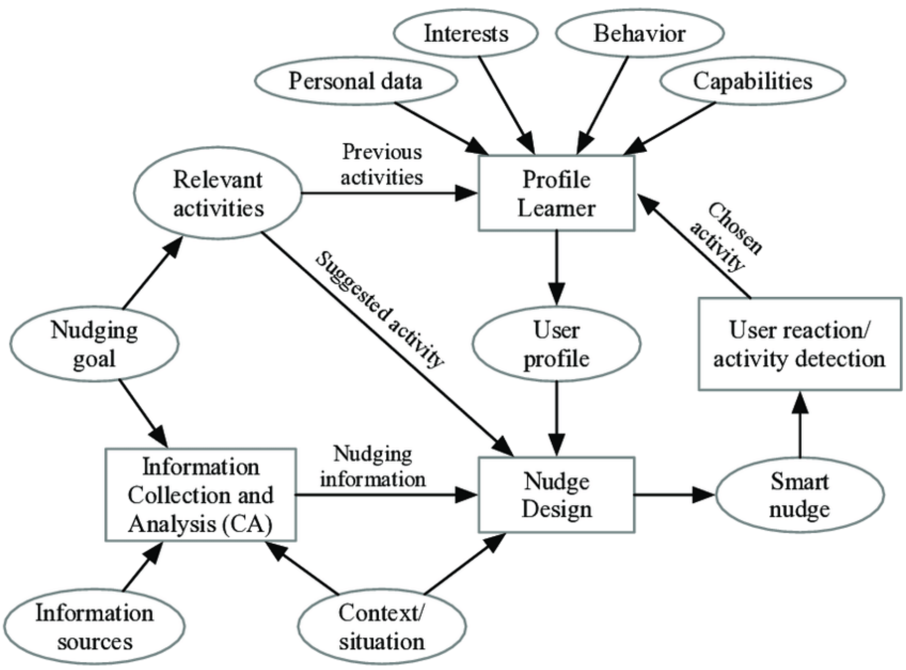

Figure 2.2: Architecture of a smart nudging system[3].

The first activity to be preformed in the smart nudging system, is defining the nudge goal. The goal is vital to determine further activities and what data should be collected[3]. The goal is then central in the creation of a user profile in the *profile learner* component. The profile learner generates a profile of the user and maps attributes, both physical and psychological, to the user and activities. The nudge goal is used in the information collection and analysis (CA) component to dictate relevant information. The mission of the CA is to collect and analyze data and provide the *Nudge Design* component with relevant information so it can construct nudges. Such information include both nudging information and user context information. Nudging information is practical data used to inform and motivate the user towards selected activities. An example of relevant nudging information is the bus table from the user's house to work, which presents the user with an alternative to driving to work. This both presents the user with practical information about an alternative, and can be used to motivate the user with information about time saved in traffic. User context information is user information that maps the situation the user is in and that of future events[3]. For example, calendar and location can be used to predict opportunities to when to nudge the user.

With the collected and analysed information, the nudge design component can create personalized nudges. Due to the user context information can nudges be tailored to a user, and suggest an activity with the nudge goal in mind. The nudge design component must consider things such as when, how and what to nudge. Timing and relevance of the nudge is important, as persuasion is mostly likely to increase both the ability to motivate the user if done right or irritate the user if done bad[4].

The last component in the smart nudging system is the user reaction and activity detection component. When the nudge design has nudged the user, it is valuable to known how it was received by the user. Did the user actually perform the activity or did the nudge irritate them? Or the nudge was not even noticed? Monitoring can create valuable insight into the reaction and action performed by the user. The insight from monitoring is then used as an input in the profile learner to adjust activities[3]. Feedback can measure the effectiveness of a nudge, and is vital to tailor and create more personalized nudges in the future.

The smart nudging system designs nudges with the help of personal and context-aware information trying to create relevant, tailored and effective nudges. Each component helps to expand the knowledge base about the user and tries to map the user motivation, opportunity, interests, behavior and other characteristics to tailor each nudge[3].

2.1.4 Ethics and Transparency of Nudging

There are several possibilities in framing a decision, as well as to influence the users in their decision-making through the use of different techniques and tools[9]. Nudging is one such concept that uses different techniques, some seen in Table 2.1, to steer the user in a certain direction. By attempting to influence the behavior of people, may nudging be subject to the evaluation of ethical concerns regarding the implemented techniques. Main concerns include the level of interference, manipulation of users and transparency on applied nudging techniques.

One concern with any system trying to influence the decision-making process is the degree of interference. How much does the system interfere with existing choice architecture and how aware is the user his interference? Some might argue that any interference can be viewed as manipulation and unethical as the original choice architecture has changed. Thaler and Sunstein,[1] on the other hand, argues that nudging can be considered an ethical influence as the freedom of choice is intact. Nudging differs from other persuasive systems, designed to influence user choice, as it does not allow any form of coercion or deception[3]. Nudging presents all choices to the user, but provides additional information to guide the user towards a certain choice. While some think this additional information is some sort of manipulation, research has suggested that humans, as non-rational decision-makers, would require guidance in the decision-making process[9].

Others support the use of nudging due to the freedom of choice being intact, but likewise argues that the use of nudging should only be applied when trying to reach a beneficial goal for both society and the individual[4]. This raises the questions of what and who can define such a goal. For example, may it be beneficial for the government to enroll all tax payers by default into a pension program, while individuals might disagree saving their own pensions in stocks or other investments. Defining what is the beneficial choice or common goal for a user might not be synonymous with that of society.

It is important that designers of persuasive systems think about the ethical implications of designing a system, and to ask both ethical and practical questions when using persuasive techniques in the system[4]. When designing a system or constructing nudges should transparency and openness be practiced, as it can act as a defence against manipulation[3]. Transparency and openness will help ensure the user's right to the applied techniques, which is trying to influence their choices. By practicing transparency can the designers of such systems be subject to public review and help better the nudge and the system[12].

With digital and smart nudging, additional ethical issues arises from the introduction of digital tools, environments and data. This is especially the case in smart nudging, which rely on personal and context-aware data to nudge the user. Privacy is a major issue, as well as to what extend one should use personal information about someone to influence their choices. By creating a user profile and knowing their personal goals, it can be easy to present information in a way that appeal to the user, and that without the user realizing it. Users are often more perceptible towards computer systems which are perceived similar in personality, and which display social cues that motivate and encourage[4].

Computer does not really have a personality, but by applying social cues learnt form a user profile, users perceive the machines almost as humans. One example of such human like system, is Eliza, the computer therapist. Even when aware of the program being a computer, people treated and responded to Eliza as a human therapist[4]. Such use of social cues should raise questions about ethics for designers of such systems.

Openness and transparency should be practiced when interfering with the decision-making process of a user. Users should have knowledge about the techniques applied and designers should consider ethical questions in their designed systems.

2.2 Edge Computing

Edge computing is a paradigm about bringing storage and data processing closer to the edge within a distributed system. This paradigm aims to achieve lower latency, higher bandwidth and more privacy by limiting the distance from production of data to the processing and consumption of data[7].

Edge computing presents an answer to the challenge of processing the vast amount of data, produced by electronic devices and sensors, within a timely fashion[7]. With the amount of IoT devices increased, and Cisco predicting that over 70 percent of the global population will have mobile connectivity by 2023 [6], will edge computing help battle the growing need for data processing. IoT devices and smart devices, such as LED lights, cameras, smartwatches and temperature sensors has increased[6] and are already present in many domains, such as healthcare, transportation and security. Edge computing aims to utilize existing capabilities in data processing and take advantage of the proximity to data in embedded systems to solve the issue of bottleneck computation, commonly seen in distributed systems[7].

An edge or edge node is any component performing computations or storing data closer to the location where the data was generated. In comparison, data normally is collected at the edge, then transferred over a network connection to a larger server performing the computations and then back again, with results being presented to the edge node. With consumers being producers and data often being created at the edge of the network as applications become more location-aware[14], data transfer seem slow and unnecessary. Edge computing aims at taking advantage of this shift in production of data[7], and the innovations in smart device technology, to more efficiently collect and process data.

With edge computing limiting data transfer over a network, it offers lower latency, but also contributes to privacy. Unnecessary uploading of data in a network increase data traffic and makes data vulnerable for hacking. If data that is user specific and personal is processed by the user device itself and restricted to that device, no sharing with a cloud or server is needed, and the risk of losing personal data is limited. That said, privacy issues with IoT devices and networks are known for running security risks. Previous examples of exploiting smart devices for eavesdropping are Google home and Amazon Alexa[1].

Heterogeneity is one of the main challenges in edge computing. The integration of multiple different devices and components, within a system, can create a need for interactions and communication between devices that uses different protocols[14]. Edge devices can interact across multiple wireless technologies, like Wi-Fi, 4G, 5G, increasing the complexity of the system. Issues like load balancing, data privacy, interoperability and resources sharing makes the cooperation between heterogeneous edge devices challenging[15].

Due to the mobility often offered by edge devices could data be collected from different locations, creating challenges in the processing of that data[7]. The system needs to manage multiple devices, where each device needs to be able to discover available resources as they move around[15]. The challenge is to do this seamlessly and efficient.

2.2.1 Fog Computing

Fog computing and edge computing are often used interchangeable as if they are the same concept. Although definitions develop from different perspectives[16] and the distinction is not generally agreed upon, this thesis chooses to define edge computing as a computing paradigm, and fog computing as an edge

1. https://www.srlabs.de/bites/smart-spies

computing architecture. Though they both want to achieve edge computing, can fog computing be viewed as a superset of edge computing, complementing the cloud computing paradigm as well[17, 18]. Fog computing concertize the edge computing paradigm into more than just an idea or concept, and provide some defined components, a structure, as well as an architecture for the implementation of an edge computing system.

Fog does not only operate at the edge, but it is an end-to-end architecture, meaning it can benefit from finding commonality within a system and also focus on integration within the whole system. Some suggests that fog computing can also be viewed as an extension of cloud computing, as the architecture can consists of computation, storage and network communication between end devices to a cloud service provider[19]. Due to limited resources and storage opportunities on smart devices, can a cloud with elastic resources benefit from the fog computing architecture. With this in mind, can fog computing be defined as an architecture that use edge devices and its resources to perform computations, while communicating and distributing data over a network to a cloud when beneficial[19]. OpenFog consortium, consisting of some of the largest technology companies in the world, provide this definition:

> "*A horizontal, system-level architecture that distributes computing, storage, control and networking functions closer to the users along a cloud-to-thing continuum[20].*"

One main characteristic of fog computing is the use of edge device resources to perform computations. By using edge device resources can the computational work be distributed and take full advantage of available resources[19]. The advantages found in edge computing, such as resource distribution and proximity to data, also provide efficiency and decrease latency in fog computing. From the cloud computing perceptive, fog computing gains agility[19]. With a cloud in fog computing, the resources are able to scale rapidly and information sharing amongst multiple user is possible, compared to keeping all information on edge devices.

The most fundamental question of the fog architecture revolve around the integration between fog nodes, things(IoT) and the cloud[21]. This raises challenges on how to distribute computational work and storage efficiently, and securely between them.

Fog systems presents security challenges with fog nodes operating closer to the edge in more vulnerable environments and often possessing less resources to protect themselves[21]. Further, by transferring data between nodes to the cloud to distribute the work, exposes data over a wireless connection making it vulnerable towards attacks. The strengths of fog computing being scalable by introducing a cloud, also makes for challenges in security and distribution of workloads of the system.

2.2.2 Cloudlet Computing

Cloudlets are an offloading layer between the edge and cloud. They aim to minimize the processing sent to the cloud and avoid issues with heavy computations in edge nodes and on smart devices. As applications are becoming more resource intensive, mobile devices are struggling to keep up, with their limited battery-life and memory which restricts the computational capacity of the device[22]. Cloudlet, essentially being a "data center in a box"[22], allows for faster processing, higher bandwidth and unnecessary use of edge device resources, such as battery-life and memory.

A cloudlet is a smaller cloud located closer to the mobile users, as an alternative for accessing a distant cloud, and can be connected to through wireless networks[22]. Cloudlets are positioned closer to the end of a system and the edge providing support for edge devices with extra storage and computational power[7]. Cloudlets works as an offloading unit to ease the pressure on mobile devices for research extensive applications.

The main challenge for cloudlets is their fixed positioning with the inability to move. With a permanent stationed cloudlet users will have to be within reasonable distance to benefit from their off-loading and memory storage. Unavailable cloudlets, due to distance, forces data transfer to be directed to a distant cloud instead. Therefore, losing the initial faster data transfer and processing offered by cloudlets. Additionally, due to being dependent on Wi-Fi, cloudlets are limited in possible placements. Cloudlets are restricted in use as they need to be positioned close to users and will face challenges if there is inadequate Wi-Fi coverage[23].

2.2.3 Multi-access Edge Computing

Previously standing for Mobile Edge Computing, but changed to Multi-access Edge Computing (MEC) as it is not limited to mobile devices only, but also other smart devices. The European Telecommunications Standards Institute(ETSI) defines MEC as:

> "*Mobile-edge Computing provides IT and cloud-computing capabilities within the Radio Access Network(RAN) in close proximity to mobile subscribers[24].*"

MEC is considered an network architecture within the edge computing paradigm, but due to the cloud computing capabilities offered can also be viewed as a subclass in cloud computing. Mobile cloud computing (MCC) faces challenges with high latency, security and lagged data transmission due to the increase in requests as IoT is emerging[23]. MEC on the other hand, extends cloud services to the network edge and allows for direct mobile traffic, connecting the end-user to a close cloud and edge network, and this way deals with challenges in MCC[23].

Characteristics for MEC as defined by ETSI[25] are:

On-Permises - MEC can run isolated, but still have access to network resources. This make it less vulnerable, as the MEC platform can be segregated from other networks.

Proximity - Having proximity to the network and directly to the device can benefit MEC with demanding computational services and data analysis.

Lower Latency - Closeness between edge service and end devices reduce latency, which makes for faster processing and improve user experience.

Location Awareness - By using low-level signaling for information sharing can edge devices discover the location of other connected devices.

Network Context Information - Real-time network information provide applications with context-related services about the mobile experience. Developers can better understand and adapt their applications.

Major challenges with MEC evolve around the sharing of network, creating issues with privacy and security. MEC consists of a less isolated environment which makes it vulnerable for malicious activities. For example, can different users connect to MEC network and perform malicious activities, like submitting false values or information to the system[23]. To tackle many of these security issues can encryption or other security strategies be used, but this will most likely decrease the performance.

2.3 Cloud computing

Although there are numerous definitions of cloud computing, the one from National Institute of Standard and technology is seen to cover the key accepts of the term cloud computing. The definition goes like this:

> *"Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction."[26]*

A main incentive for the emergence of cloud computing for business was the cost efficiency[27]. In cloud computing may a user only pay for the resources in use. As service providers are responsible for the provisioning of resources on-demand making making scalability easy. There is no longer a need for businesses to invest in too much or expensive data hardware before knowing the necessary resources. The scalability of resources limits the initial investment, one pay only for what one uses and the service providers are responsible for the fault tolerance on resources.

Further, is easiness and the level of abstraction a contributing factor for users choosing to run or develop their applications and systems in the cloud. Different service models offers different levels of abstraction and replace complexity with simple user interfaces to work with[27].

Cloud computing is a computing paradigm for distributed systems where computing resources are provided from a service provider, or oneself with different degrees of deployment and resources. The three service models which service providers in cloud computing offer are platform-as-a-Service (PaaS), Software-as-a-Service (SaaS) and Infrastructure-as-a-Service (IaaS) and determine the amount of resources that the service provider is responsible for.

Software-as-a-Service (SaaS) is when the cloud service provider deliver a software to the user running on the cloud. The user cannot control any underlying infrastructure, but only use the software available.

Platform-as-a-Service (PaaS) is when the cloud runs all underlying infrastructure such as operating system, network and servers, and the user use this infrastructure to run their application on top. The user is responsible for the software to work, while the cloud is responsible for all resources.

Infrastructure-as-a-Service(IaaS) provides the user with control over resources such as operating system, some network components, storage and deployed applications. The user can control, deploy, provision and run software, operating systems and applications[26].

Deployment models determine the degree of sharing resources on a physical level. The name cloud gives the illusion of being in the sky, but it resides on physical hardware somewhere in the world. Hardware is generally server racks hosting multiple organizations, businesses, and individuals simultaneously. The deployment model determines if users share hardware by being on the same server rack, or run software on isolated hardware for only one customer.

Private Cloud is used exclusively by one organization. It can be operated and owned by either the organization or a third-party or both in a combination.[26]

Community Cloud exclusively to a certain community. These share a common concern, but might be from different organizations. The cloud can be operated and owned by either the organization or a third-party or both in a combination.[26]

Public Cloud is a open cloud to be used by the general public. It can be managed by one or multiple organizations like business, government or academic institutions.[26]

Hybrid Cloud is a cloud with a combination of public, private or community deployment model. Each entity shall remain unique, but are integrated such that data and applications can be shared.[26]

Although each service level and deployment model offers flexibility and control of the placement of data, the issue of security is often an obstacle for cloud computing users. The concept of letting a third-party have responsibility for your application or system is unacceptable for many businesses and users. Letting service providers handle your resources also means them addressing potential security issues, such as data loss and phishing[28]. Phishing is when cyber attackers try to obtain sensitive information from users by posing as a legitimate organization or individual[2]. Phishing emails are common, telling users to reset their password or give up their credit card information. Additionally, as deployment models open up to users to share physical resources and reside on the same resource, such a multi-tenant model might provide side channels for hackers to run malicious software on shared hardware[28].

Another issue to consider is that of the cost of cloud computing. Cloud computing may be cost efficient when considering the initial investment saved on resources, but communication and costs pr unit is likely to be higher when in use[28]. Considering the security issues of a shared cloud might incentivize businesses to pay more for better security and increase the cost of running the application. An option is for a company to distribute data in both public and private clouds, distributing sensitive and non-sensitive data according to the security level in the cloud. However, the use of different clouds might arise new issues with integration and increase in complexity which can increase the

2. https://www.phishing.org/what-is-phishing

cost, both in terms of time and money[28].

2.4 IoT and smart devices

IoT and smart devices have brought advanced technology into everyday life. The number of devices has seen tremendous growth in the past years[6], both in the workplace and at home. The variety offered in devices and sensors provides personal and customizable solutions at an affordable cost for various problems within multiple sectors.

Smart devices are digital devices capable of autonomous computing, which can communicate and interact with other smart devices and users[29]. Examples of such smart devices are temperature sensors for detecting fires, light bulbs that turn on based on movement, or a GPS tracker for dogs. In comparison, refer the Internet of Things (IoT) to the use of "things" or "objects" such as sensors, mobile phones, tags and other smart devices, which can communicate and interact within a network towards a common goal[30]. Smart devices are the physical "things" present in the IoT. However, both terms are generally used interchangeably regarding the behavior of smart devices.

IoT are transforming industries and increasing revenue, through the use of smart devices to optimize business processes[31]. Usage of IoT can be divided into three main categories for enhancing customer value, monitoring and control, big data and business analysis and information sharing and collaboration[31].

Firstly, monitoring and control contribute to safety and lower costs. For example, an IoT uses sensors to monitor energy consumption, identifying points of high usage. On the other hand, can the IoT system control and provide a mechanism to turn off power in the event of over-consumption. Monitoring the elderly in need of assistance, the heart rate of professional athletes at risk of heart attacks, and control systems to keep cars on the road are all examples of IoT contributing to safety.

Secondly, IoT provide vast amount of data being used in big data and business analysis. Collection of information can contribute to decision making and provide more personalization. For example, Oral-B observed an increase in brushing time with the use of personal and interactive electrical toothbrushes. Records of brushing times and habits provided enough information to conclude an analysis, generating tips for each user[31]. Lastly, with IoT can information sharing happen between users, things or both. Information sharing can enhance collaboration, situation awareness and avoid information delay[31].

For example, grocery stores can provide customers with recipes, discounts and coupons based on location tracking from smart devices.

With the increase in IoT devices[6] have the amount of data grown massively creating challenges as data needs to be processed and stored. Generally have IoT devices limited resources, increasing network traffic as data is sent elsewhere for processing and storage. Further, the restrictions and limitations of IoT devices in regards to computational power and resources have introduced security concerns[30].

The risk related to simple IoT devices have gained public awareness with reports on of security attacks against commercial IoT devices[32]. Part of the challenge is generally inadequate or non-existent security mechanisms due to limited resources. Additionally, the variety in IoT devices require a variety in the implementation of security mechanisms. Heterogeneity of devices and communication protocols complicates the development of general security schemes[33].

2.4.1 Sensors in Smartphones

Smartphones are powerful tools in the IoT world with their significant resource capabilities. An increase in smartphone capabilities from earlier generations has evolved, creating lightweight, mobile devices with resources to compute and store a decent quantity of data. Huge market share made by smartphones in the telecom sector has driven innovation due competition between big companies like Apple and Samsung [34]. In addition, significant upgrades to both hardware and software have made smartphones convenient and powerful general-purpose objects.

Innovations have left modern-day smartphones with a significant variation of sensors providing customers with features, such as a step counter, GPS and heart rate monitor. A sensor can be defined as:

> " *A sensor is a device that converts a physical phenomenon into an electrical signal. As such, sensors represent part of the interface between the physical world and the world of electrical devices, such as computers.[35]*"

Sensors monitor and detect changes in their environment and transfer this information to a computer for processing. Within a smartphone are there multiple sensors already, decreasing the need to communicate with additional computers.

Android phones have categorized device sensors into three domains, motion, position, and environment. Motion sensors report on the motion of the device, like an accelerometer and gyroscope. Position sensors include a geomagnetic field, which helps determine the device's position in the physical world. Lastly, are environment sensors providing measurements of various environmental properties such as light, temperature, pressure, and humidity. A selection of sensors offered on Android devices[3] are presented in Table 2.2.

Sensor	Explanation
Accelerometer	Measure applied acceleration force from all physical axes, including gravitational force.
Gyroscope	Measure the rate of rotation of a device's physical axes.
Heart rate	Reports the value of heart rate as beats per minute.
Light	Measures the level of ambient light in lux.
Relative humidity	Measure the relative ambient humidity in percent.
Step counter	Reports on the number of steps detected for the device.

Table 2.2: A selection of sensors on Android devices.

3. https://developer.android.com/guide/topics/sensors/sensors$_{o}verview$

3

Related Work

This chapter presents related work and research on edge computing used in nudging systems. In addition, due to the limited research found on the subject, is research on recommender and monitoring systems also included. Recommender system is a persuasive system like nudging with a parallel end-goal of influencing users. Hence, recommender systems can provide similar insights into the future benefits and challenges for edge computing in nudging. Next, monitoring systems have similar demands and requirements as a smart nudging system. Techniques applied to monitoring systems utilizing edge computing provides suggestions for a smart nudging system to use similar techniques and methods.

3.1 Edge computing and Nudging

Limited research links edge computing and nudging. Andersen et al.[36] present edge computing in particular components in a smart nudging system for green transport choices. Stirapongsasuti et al.[37] present an implemented nudging system with edge processing and storage, but is limited to a stationed edge device in the scenario to improve hand hygiene. However, research on the subject suggests that edge computing can provide low latency and privacy in real-world scenarios.

Andersen et al.[36] present components with fog computing, as part of the smart nudging architecture, to help influence users towards green transport choices. With personal and situation-aware data provided to users, Andersen et al.[36] hope to battle issues with transportation and transportation infrastructure. Fog computing is a beneficial paradigm for the sense, inform and nudge components to handle edge data processing. Edge nodes' benefits include lower latency, privacy, greater context-awareness, and higher availability. On the other hand, it is suggested that challenges like lack of global knowledge, weak edge nodes, and unpredictability in mobile environments may be of concern. Andersen et al. [36] make a case for edge-processing in a smart nudging system to help with IoT data and make use of situation awareness when data is processed closer to the edge of the network. However, the contributions of this research are primarily the description of a smart nudge architecture and its components. Therefore, an implementation is not presented, and also edge computing is not the primary paradigm for the system architecture but rather a suggestion among other architectures. In comparison, this thesis provides an actual implementation of a smart nudging system that focuses on utilizing edge resources. The implementation is built around the scenario to improve physical activity, rather than green transport choices. However, the system design presented in this thesis is generalized to accommodate different scenarios.

Stirapongsasuti et al.[37] implemented a nudging system on an edge device, encouraging people to use hand sanitizer in private organizations. The edge device, a mini-PC, was responsible for ensuring privacy-sensitive data aggregation from the collected data, such as facial recognition and time of entering and leaving the building. The intent of using IoT was to compare the effectiveness of none digital and digital nudges and their ability to change hand hygiene behavior. Stirapongsasuti et al.[37] conducted four case studies to investigate the effects of different nudging implementations using a footpad sensor for frequency, PIR sensor for motion detection and facial recognition for detecting specific participants. Results showed a significant increase in the user frequency of hand sanitizers when using nudge-based methods[37]. Furthermore, benchmarks confirmed the system's sustainability, ensuring that the implementation can operate with few edge resources and that the edge device can operate without delay. However, Stirapongsasuti et al.[37] put forth that different edge devices and methods might be more appropriate for use in a smart nudging system. Nevertheless, results conclude that using a mini-PC is a feasible edge device, lightweight, and capable of performing operations that are applied in a real-world scenario. However, the contribution made by Stirapongsasuti et al.[37] is limited to digital nudging performed by a stationed device for improving hand hygiene. In contrast, this thesis proposes a smart nudging system utilizing a mobile edge device. The discussion in this thesis will focus on mobile edge devices' benefits, as tailored nudges demand personal data collection.

3.2 Recommendation Systems

Recommender systems have the same mission as nudging systems; using personal information to influence user behavior. However, recommender systems do not practice freedom of choice, instead it filters out the options that are considered irrelevant for the user. Nevertheless, research on recommender systems might offer insights into optimization technologies and challenges with edge computing, as both systems have similar approaches. Tsolakis et al.[38] and Sayed et al. [39] both aims to use edge computing to change energy consumption behavior.

Tsolakis et al.[38] present an approach for delivering user-tailored context at the appropriate time using a recommendation engine and lightweight AI-driven edge computing algorithms on users' mobile devices. Tsolakis et al.[38] aim to influence users' energy-related behavior in tertiary buildings with a user-centered approach to battle the issues of sustainable energy production and consumption. The approach called SIT4Energy has data generated by sensors pushed to a cloud database running the recommendation engine. The engine is responsible for recommending the most appropriate context for a specific user. It needs to consider the cloud database with sensor data against the current consumption and the user's energy-related behavior. Further, the selected recommendation is pushed to a mobile app for end-users. The edge device uses an AI-driven time-dependence tool to present user-tailored context at an appropriate time. Results from deployment in real-life university offices show that a positive impact has been made. In SIT4Energy, edge devices provide context-aware data as sensors and deliver recommendations through a mobile app. However, the cloud, centered between the sensors and the user's mobile device, provides data analysis and storage for the system. Therefore, the approach achieves context-awareness with sensors but does not investigate the utilization of edge device resources as data is processed mainly in the cloud. In comparison to SIT4Energy, is the edge device the system's primary processing and analysis component in this thesis. Both systems gain context-awareness from IoT devices, but only this thesis investigates the potential benefits of performing computational work primarily on the edge device. As a result, the edge devices perform little computational work in SIT4Energy, and the approach does not consider the latency and processing benefits gained for edge devices.

Sayed et al.[39] aim to present an energy-efficient framework as a home-assistance platform with the use of edge computing. First, sensors about energy activities are collected and pre-analyzed before being sent to further back-end analysis, running the home assistance software. The home assistant then filters out data, running on a raspberry pi, before recommendations are sent as notifications via a mobile application to influence behavioral change. Results from a deployment at the Qatar University campus suggests that the framework can promote users' transition to new consumption patterns. However, future work includes expanding the system to accommodate multiple users. Sayed et al.[39] present an edge-based monitoring and recommender system trying to influence energy-saving behavior. The system utilizes the end-users edge devices, but only as the deliverer of nudges. In contrast, edge devices are the primary data collection and processing component in this thesis. Arguments about latency and privacy by utilizing edge devices are made by Sayed et al.[39] similar to this thesis. However, gains from personal data collection by using edge devices are not discussed.

3.3 Automatic Monitoring Systems

Automatic Monitoring systems need to accommodate similar demands and requirements as smart nudging systems. They both look to collect and analyze data efficiently while working with personal data. The different systems also require context-aware data to create relevant feedback or recommendations for the user. However, monitoring systems might not deliver feedback directly to the user but rather a caregiver or security personnel instead. Research include a fog and cloud model for healthcare monitoring of elderly in a 'smart-environment'[40], and an implementation of a cloud-edge architecture for air quality monitoring[41].

Moore and Van Pham[40] present a model for a healthcare monitoring system incorporating FOG and cloud-based computing to achieve low latency and big data analysis. The system is meant to tackle the challenges of an increasingly elderly demographic in need of healthcare assistance, especially regarding illnesses such as Alzheimer's and dementia. Moore and Van Pham[40] propose a FOG computing model to extend the conflation of smart-home and smart-city into a smart-environment. Patients dynamically change context and a smart environment must monitor situational awareness relating to a patient's location both outside and inside the home. Moore and Van Pham[40] propose a monitoring health system and suggest two real-world scenarios to which it may apply. The model addresses issues of low latency, real-time data processing, big-data analysis and in-memory and persistent storage. Furthermore, the model includes heterogeneous sensors sending data to the FOG, then processing it, before transferring data to a cloud. A cloud then performs big-data analysis, sometimes returning analyzed data back to the FOG, adding to a patient's prognosis and intel. Data sent to the cloud is stored locally and transferred in bulks at pre-determined intervals. This flow of data ensures low latency offered by the FOG, as data can be processed closer to the sources, as transferring data over a network to the cloud is related to performance issues.

Moore and Van Pham[40] briefly mention nudging and choice architectures as a benefit to the proposed approach by using mobile information technologies. Additionally, it is suggested that the method be generalized to other medical conditions that use monitoring. However, in contrast to this thesis is no implementation of a edge system presented. Furthermore, although mentioning the benefits of context-awareness and low latency of fog, are privacy issues with edge not addressed by Moore and Van Pham[40] like in this thesis.

Kristiani et al.[41] deployed a distributed monitoring system over the Hunghai University to research if IoT devices with the combination of edge and cloud computing can provide a rapid, light-weight and more reliable system. Using Kubernetes' minion and docker containers, as well as using container-based virtualization, edge nodes, in the form of raspberry pis, were placed around the university, communicating with Arduino sensors over LoRa. Further, an MQTT protocol was implemented for exception notifications. Finally, received data was uploaded to the cloud from the edge gateways, containing aggregated data from multiple IoT devices. Kristiani et al.[41] chose the edge computing paradigm to accommodate efficient processing needs, due to increasing amounts of data by the forthcoming of IoT and cloud. Arguments are made that the cloud is essential for the success of IoT, but on its own not adequate to perform fast data analysis[41], hence the introduction of edge computing.

The paper[41] contributes with a proof-of-concept for a large-size air-quality system, covering a whole university campus and integrating multiple sensors and edge devices. Additionally, [41] includes discoveries on the limitations of IoT devices, such as power consumption and computational processing. However, this thesis's goal to utilize mobile edge devices for data collection over a distance is not discussed in this paper. Edge nodes are only used as simple gateways to collect information and work as temporary storage. In comparison to this thesis, edge devices are used as a layer between IoT devices and the cloud rather than the primary data processing and analysis source.

4

Research Methods and Methodologies

This chapter presents the methodology used to answer the research question on what role edge computing may have in a smart nudging system. Section 4.1 discusses the difficulty of applying research methods in Computer Science due to overlapping with other scientific fields. In addition, a definition is presented of what research is. The definition helps clarify what philosophical approach is used for this thesis. Section 4.2 revisits the research questions and lists the approaches used in this thesis. The brief description of events summarizes the order in which the research happened. Section 4.3 presents qualitative research as the main research method in which this thesis will conduct its research. However, the opposite research method, quantitative research, is also represented to give insight into the alternative research approach. Finally, section 4.4 presents the qualitative research methods used in this thesis. These methods include applied research, the inductive approach, and the case study strategy.

4.1 Research in Computer Science

Research methods in Computer Science is considered hard to concertize and define accurately. This is due to the extensive coverage of the science and overlap in other fields such as engineering, mathematics, electrical engineering etc. [42]. Also the different definitions for what is research and research methods, offers more confusion to the topic. For this master thesis is the research conduct based of the general definition of research as

> "*...a multiple, systematic strategy to generate knowledge about human behavior, human experience and human environments.*"[43]

The thesis recognize the different approaches for research methods in different fields and aim for a realistic philosophical approach. This approach assumes the reality of things are known and their existence is not dependent on human acknowledgment or perception. A realist observe and collect data and facts about a phenomenon and use this to further the understanding and develop knowledge about the phenomenon[44].

4.2 Research Question

To conduct research for a master thesis should certain methods be applied to verify the validity and correctness of the research[44]. To access what research methods to apply, should the goal of the master thesis be revisited:

> *What role may edge computing have in a smart nudging system?*

The research question to be answered focuses on discovering the use of edge computing in a smart nudging system and the contributions made by edge computing. By following an edge computing architecture, a prototype will be developed to test the opportunities created by the edge computing approach. The process from research to prototype will discover advantages and problems with the architecture in a certain environment. The development of a prototype will contribute to observations of the system and lay the basis for future work. In addition, will the evaluation of the research and the observation of the prototype help formulate a conclusion to the research question.

4.3 Qualitative vs. Quantitative

To investigate if edge computing is an effective computing paradigm in a smart nudging system, should a main method be chosen. The research for this thesis follows a qualitative method as a prototype is developed. The qualitative method is about gathering research to create tentative hypothesis or the development of computer systems or inventions[44].

The qualitative method differs from its opposite known as the quantitative method as it focuses on creating a system in an certain environment. The quantitative research method on the other hand, is about studying a known phenomenon in general with different experiments either with different data or in different environments. Quantitative research tests and experiments with different approaches, while qualitative methods create theories around implementing an new invention or computer system[44].

This thesis follows a qualitative research method as the goal is to investigate a new combination of edge computing in smart nudging. The research in the thesis proposes a new invention or system called NuEdge.

4.4 Methods and Methodologies in the Qualitative domain

When a main research method is decided, should further research methods and methodologies be within the qualitative domain. Anne Håkansson[44] presents a research portal for classifying methods and methodologies to either suit research within the qualitative domain or quantitative domain. The portal also emphasize the importance of conducting certain research methods before another. For example should a case study be conducted before coding starts. The qualitative research methods and methodologies for this thesis are explained in Table 4.1.

This thesis uses the applied research method to establish the implementation of a computer system on existing research. Therefore, the thesis reviewed previous knowledge on the smart nudging system to develop a set of requirements for a successful smart nudging system. Based on these requirements was the NuEdge system developed by trying to utilize edge resources in a smart nudging system.

Furthermore, an inductive approach help formulate arguments for design choices in the NuEdge system. The thesis gathered research on edge computing and smart nudging and identified the potential benefits of edge computing in a smart nudging system. The research helps propose facts and data, used to establish a solution to the research question and develop an edge-based smart nudging system.

Lastly, this thesis is a case study as the NuEdge system was developed and investigated in a real-life scenario to observe the impact of edge computing in a smart nudging system. A case study helps identify challenges and boundaries that are not obvious from the theoretical research alone. Therefore, is a smart nudging system deployed in a real-world context to improve physical health, studying the application of an edge-based smart nudging system in a certain scenario.

Method	**Definition**
Applied research	A method for answering or solving specific questions or practical problems often derived from existing research and data from previous work[44]. With an applied research method is often the problem solved by developing an invention such as a computer system, application or technology as an answer to the problem statement.
Inductive approach	Data is generated to investigate a phenomenon or develop an artifact, the data results into establishing a reason for why something is happening[44].
Case study strategy	With a case study research strategy is the phenomenon investigates through an empirical study of evidence from multiple source[44].

Table 4.1: Definitions of qualitative research methods used in this thesis.

5

Edge Computing in Smart Nudging

This chapter examines the role edge computing may have in smart nudging. Firstly, section 5.1 reviews a simplified smart nudging architecture to discover the demands and challenges of such a system. Data collection and processing are identified as important tasks to successful nudge a user. From observing the smart nudging system architecture proposed by Karlsen and Andersen[3] has a set of main requirements for a smart nudging system been established. Section 5.2 discuss edge computing contributions both in general and in a smart nudging system. Discussions are made about using edge computing to tackle challenges addressed in section 5.1, as well as in regards to improve physical activity problems as a nudge goal. Furthermore, limitations in edge computing with regards to smart nudging demands are addressed, such as limited storage and computational resources. Then, section 5.3 takes a look at cloud and IoT to complement the edge computing paradigm in order to enhance the overall performance in a smart nudging system.

5.1 Smart Nudging System

This section revisits the smart nudging system architecture proposed by Karlsen and Andersen[3] to analyze the components and data flow in a smart nudging system. The analysis has identified four main requirements for a successful smart nudging system.

Firstly, Karlsen and Andersen[3] propose a smart nudging system to increase the efficiency of a nudge. As an extension of digital nudging, smart nudges should additionally construct tailored nudges using personal and context-aware data about the user. Karlsen and Andersen believe these tailored nudges will make the user more perceptible to a nudge, thus, increasing the number of successful nudges. A nudge is considered successful if the user is affected by the information received by the nudge.

A smart nudging system aims at constructing these tailored nudges through data collected about the environment and profile information gathered about the user. A simplified architecture for a smart nudging system is seen in Figure 5.1, focusing on the four main components; the profile learner, information collection and analysis, nudge design, and user reaction. The figure depicts the integration between the components and the flow of data. A simplified architecture has removed less vital activities to focus on the main areas for optimizations in the smart nudging system.

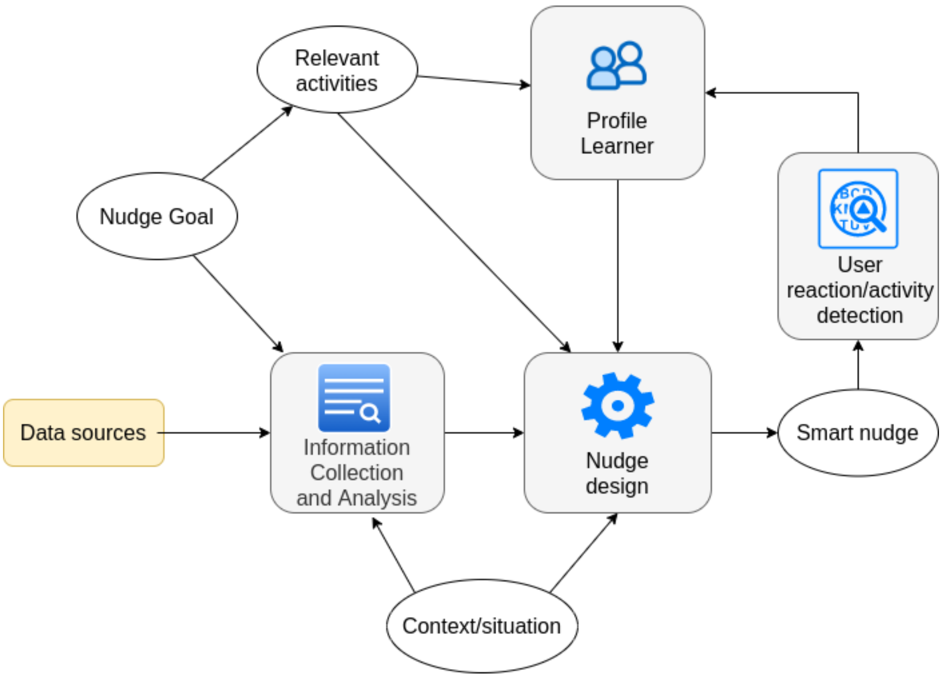

Figure 5.1: Simplified architecture of a smart nudging system[3].

One of the main functions of a smart nudging system is collecting and processing data. Data is a contributor to all main components of the smart nudging system. Data is collected to obtain a user profile, determine qualified activities, register reactions to nudges and construct tailored nudges. Information about both activity and user context should be collected[3]. For example, data about the weather, timetables, and distance may be relevant to suggesting and planning an activity. Meanwhile, the location of the user, calendar information, and step counter might offer insight into the activity's scheduling.

Furthermore, collected data needs to be analyzed and processed to determine their relevance in a tailored nudge. For example, the smart nudging system may nudge a user after work, suggesting walking to a supermarket to get dinner. Data about working hours, distance to the supermarket, and the user's preferred dinner choice needs to be collected and processed to determine their relevance. Collecting and efficiently processing data is essential to the success of a smart nudging system.

5.1.1 Requirements

Certain requirements should be fulfilled when designing a smart nudging system. Identifying data collection and processing as one of the most important tasks helped determine four main requirements for a successful smart nudging system.

Personal data and Context-awareness - A nudge needs to be tailored to the user, ensuring more efficient nudging[3]. Data needs to be combined or anchored with contextual information to determine the environment and situation in which the data is placed[45]. For example, a temperature is of no value without the location from which the temperature was recorded. Context ensures more efficient personalization[45], and personalization ensures more efficient interactions between the user and the machine[4].

Data management of heterogeneous sources - Data should be able to come from different sources and still be handled by the system. Data management of a smart nudging system should support collecting, processing, and storing of various data. For instance, a tailored nudge might utilize temperature data from an IoT device, steps data from a smartphone application, and hiking routes for a specific location provided by a cloud service. Together all these resources provide a more extensive analysis of the user and the environment in order to create more successful nudges.

Efficient processing - Efficient processing is essential for the validation of a nudge. Efficient meaning processing data within a timely fashion, so data is neither outdated nor irrelevant.The relevance of data might be limited to milliseconds, requiring efficient processing. Furthermore, some data is only valid when presented at the right time. For example, collecting temperature data during hiking is only relevant for the user during the activity. Therefore, it is crucial to efficiently process and filtrate data before being used in a nudge.

Privacy and Security - Whenever working with personal data in a smart nudging system, the data needs to be protected. Security measures should be taken to ensure privacy and prevent unauthorized tampering with the data. While privacy can be viewed as the user's right to control who has access to their data, is security the means to enforce that right[46]. Privacy is of great concern in any system, especially in a smart nudging system as one is working with personal data used to influence behavioral change.

5.2 Edge Computing in Smart Nudging

This section discusses the potential benefits and challenges of utilizing edge computing into smart nudging. Additionally, relating the edge computing benefits to a real-world scenario; that of improving physical activity. Edge computing offers personalization and context-awareness, lower latency, and contributes to privacy. However, it may not provide enough computational power or storage demanded by a complex smart nudging system.

5.2.1 Benefits of Edge Computing

One of the main benefits of edge computing is to utilize edge resources in a network to process data more efficiently. A system will benefit from employing these often-used resources, and lower latency by processing data closer to the user and edge. Doing processing of data on the edge, limits unnecessary exposure of data and contributes to privacy.

The evolution of smartphones has enhanced edge device capabilities to be responsible for data storage and processing within a system. Over the years have edge devices rapidly evolved, increasing resources and capabilities to meet the increasing demands for efficient data processing. For example, while earlier generation smartphones had 128MB[1] of storage capacity, newer smartphones commonly have a staggering 128GB[2] of storage with the opportunity to expand

1. https://www.gsmarena.com/o2$_x da_i is - 933.php$
2. https://www.gsmarena.com/samsung$_g alaxy_s 22_5 g - 11253.php$

it further if needed. Smartphones have become personal computers used by everyone as part of everyday life. Smartphones are no longer just for texting and calling, but have become a general-purpose device. The fastest-growing market in the telecom industry in 2013 was smartphones, responsible for over half of the market[34]. The significant market size has businesses competing for a market share, stimulating rapid innovation and frequent smartphone upgrades.

By utilizing all available resources in a system, processing can be performed faster. Edge computing argues that the potential of edge device resources are not being exploited. For instance, in a typical client-server architecture, data is requested by the client while a server is responsible for computing and data. In edge computing, edge devices are responsible for performing some of the system's computational workload. An edge device may be a simple client in many systems, not responsible for computational work. Hence, such systems are not utilizing all available resources. Edge computing recognizes the potential of assigning some or all work to edge devices to distribute the workload and utilize all available resources.

Being on the edge device, the closeness to where data is produced and processed decreases latency. For example, a step counter sensor within the edge device can help determine physical activity instead of requesting and uploading data to an external step counter application. Edge device processing removes the standard step of transporting data from and to other data sources. In addition, as consumers are becoming producers of information, data can be accessed closer to the source. For instance, the sharing of images or activity data produced on an edge device can be pre-processed before being uploaded to the internet. The edge device is responsible for creating and maintaining the image and step count data produced by the user. Edge device processing, where data is produced and consumed, decreases transfer time and distance.

Edge computing contributes to privacy with limited data exposure due to local processing. By utilizing the resources on the edge device, keeping everything within one device prevents the intervention of other systems or devices. Not transferring data over any connection or sharing it with other devices avoid exposing data unnecessarily and making it vulnerable to malicious activities. For instance, transmitting data over Wi-Fi outside of work or at home may not have the proper security mechanism, like encryption, to ensure a safe data transfer. Users often connect to public Wi-Fi as it is accessible and free when out in public. Unfortunately, public Wi-Fis are vulnerable because they are open to anyone, also allowing hackers to join. Keeping data contained on the edge device and limiting data transfer will limit the hackers' opportunities to access the device and also its data. However, a system would benefit significantly from including other devices as data sharing is essential in distributed systems.

Hence, privacy is not ensured but storing part of the data on a single device, but limits access for other users, contributing to privacy.

5.2.2 Challenges with Edge Computing

To perform all computations on an edge device might affect the user experience due to limited edge resources. For example, using a smartphone as a personal assistant with calendar appointments and road directions throughout the day takes a toll on an edge device's battery life and storage. Lack of storage restricts what the user can store and may limit the implementation of particular security mechanisms. On the other hand, lack of power eliminates the use of the edge device.

The phone industry has challenges with keeping the specifications of a smartphone high while accommodating the convenience of use and mobility by minimizing the size of the physical phone. Even with the increase in hardware in smartphones, the evolution of batteries struggles to keep up with users increasing smartphone usage. The introduction of lithium-ion batteries has increased battery time, but upgrades to lithium-poly-ion batteries are still rare. Storage and battery improvements are currently available but not generally available for the average consumer due to cost[3]. Systems of a certain size might require additional support for processing and storage as edge device resources are limited.

Another challenge with edge computing is resource sharing within a system. Resource sharing between edge devices may be complex and increase latency as communication demands grow. An edge device can perform computational work and store data locally, but it would be inefficient if all edge devices were to do it on the same data. For example, may multiple users request the bus table for the same location. All edge devices perform the same request and store the same data. Therefore, should data be shared between edge devices in a system to avoid redundant processing and storage. Data located on one edge device may be useful data for another edge device and user. However, not having a centralized unit for communication and storage makes mapping edge devices and their data complex. Distributing workloads between devices demand communication, which will increase latency and make processing on edge inefficient.

3. https://blogs.windows.com/devices/2011/05/25/power-up-the-amazing-evolution-of-the-cellphone-battery/

5.2.3 Edge Computing in a Smart Nudging System

As personalization and context-aware information are the primary sources in constructing tailored nudges, a smart nudging system would benefit from personal edge devices for data collection and processing. The amount of edge devices worldwide makes edge computing convenient and available for personal data collection. Furthermore, such devices are often wearable, providing mobility to collect data about different environments. Mobile devices may follow a user throughout the day, providing significant data and context-awareness to a smart nudging system.

Edge computing enables the use of edge device resources to perform the processing and storage of data. The number of devices has increased significantly over the years and is predicted to keep rising[6]. Therefore, one can assume that most businesses, organizations and individuals have some sort of device available to perform or store data. The high availability of devices can indicate significant coverage for a smart nudging system. For example, if the smart nudging system resides on an edge device, it is available for all users with an edge device. Edge devices are therefore convenient for processing and storage due to the high availability.

Furthermore, a significant amount of users have personal edge devices. In edge computing, such edge devices can often be the user's, serving as a convenient and cost-effective data processing and storage solution. The system is not dependent on hardware such as a server to store or process data but can rely on the users' already existing resources instead.

In addition, the use of personal edge devices contributes to the collection of personal and user-specific data. For instance, research shows that users average about 5 hours every day on their smartphones[47]. A smart nudging system can get insight into the user's habits from the interaction between the user and his or her device. For example, the system may learn that the user always scrolls on their phone for 20 minutes after dinner. The smart nudging system can then nudge the user right after dinner to go for a walk based on that interaction. Lack of interaction also gives insight into the habits of the user. For example, data on inactivity can be analyzed to identify sleep patterns or work hours for the user. Personal edge devices stay close to the user and its environment being able to give accurate and efficient data collection to a smart nudging system.

A smart nudging system will have more efficient processing from collecting, analyzing, and delivering nudges all on the same device. Data collected straight from the user will save processing time, not having to request the information from another data source. Instead of sending data to be analyzed elsewhere is data processed and collected on the same device. Limiting data transmission contributes to lower latency. Low latency means the analysis and processing of data can happen faster. Local storage of data in the device makes it efficient to perform analysis as data share storage location and is close to the data. By being on the same device is the data transfer limited, hence more efficient processing, delivering nudges quickly to the user.

Being on the edge device can data be locally processed or pre-processed to determine the relevance of data before being sent further to other components in need of the data in the smart nudging system. Edge devices may have storage limitations and struggle with the extensive data required by the smart nudging system. However, the edge device can help determine the relevance of data beforehand and save processing time. By preprocessing, data can the edge device be evaluated, before sending it to storage or for more complex analysis. Pre-processing on the edge device, where data is collected, can limit data storage on the destination storage location by filtering out irrelevant data. The edge device can work as a gatekeeper to the smart nudging system to provide more efficient processing or pre-processing in a smart nudging system.

A smart nudging system may benefit from the mobility of edge devices. Having the opportunity to transport devices easily, even wearing them, contributes to the tailoring of nudges. With a wearable device, the user can be monitored throughout the day, collecting information about the user and its environment. For example, a smartwatch can stay with the user, collecting information about sleep patterns, workout length, and heart rate. Because the smartwatch stays with the user, it can also help provide context-awareness to some data. For instance, heart rate data can be tied to a specific location providing more accuracy or insight to why heart rate is high or low. Data about walking speed should be supplemented with the walk's location, elevation, or length to give a more accurate picture of the results. A walk may take longer, but the elevation and length of the walk can justify a lower walking speed. Mobile edge devices can provide personal and context-aware data by being worn by the user.

Furthermore, many edge devices offer customizability with various sensors and devices available. For example, sensors are available to measure anything from temperature and movement to what is in a person's fridge. Sensors can help monitor or even detect unhealthy habits or health issues. For instance, based on the frequency of bathroom breaks or sleep quality, patterns can be identified matching those commonly seen in people with constipation or sleep deprivation. Smart devices and sensors will provide a smart nudging system with specific data about different environments and variables, contributing to more comprehensive data collection and context-awareness.

5.2.4 Edge computing to Improve Physical Health

The convenience of edge computing and mobility contribute to significant activity detection and data collection in the scenario to improve physical health. For example, can sensors within an edge device contribute to detecting or monitoring the physical activity performed by a user. For instance, a step counter, heart rate monitor, or workout application gives insight into the user's physical health. Primarily can an edge device assist in improving physical health as the edge device will stay with the user and provide extensive insight into the user's possibilities and habits. For example, smart nudging a user to more physical activity can be as easy as helping the user call a friend to go for a walk according to their calendar or helping them send an email to sign up for an aerobics class based on their interests. Edge computing in a smart nudging system can collect personal and context-aware data all the time and create a comprehensive user profile to nudge users successfully towards better physical health.

5.3 Complementary Approaches

Due to limited storage and computational resources, other components may assist edge computing in providing more efficient data collection and processing in a smart nudging system. Cloud computing may assist with scalable resources with a global reach, offering the ability to share data between users anywhere in the world easily. However, the cost of running a secure cloud and trusting cloud service providers with sensitive data may be naive. A local server may be a preferred option to ensure privacy for sensitive data by limiting exposure within a local network. However, local servers are often costly and bound to a location. Furthermore, IoT and smart devices are discussed as beneficial to smart nudging, contributing to more context-awareness and increasing the variety of collectible data.

5.3.1 Cloud Computing

Cloud computing may complement the shortcomings of edge computing in a smart nudging system. While benefiting privacy and low latency with data collection and processing on the edge node, might edge computing meet limitations in the scalability of the system. Cloud computing can offer scalability in resources and data sharing between users worldwide, but faces challenges of privacy and latency with data being sent between the user device and the cloud.

A smart nudging system will benefit from the scalability of cloud computing. The cloud can accommodate the fluctuation of resources and devices in a smart nudging system with scalable resources. For instance, a smart system should be flexible to accommodate adjustments to user profiles and goals. For instance, as users achieve their subgoal of 5000 steps a day, should longer walking routes should be part of a nudge. Likewise, new activities and nudges should change accordingly as the user evolves. Cloud computing provides the resources to accommodate the new needs of a smart nudging system.

Introducing a cloud in a smart nudging system providing on-demand resources may be costly, but so is providing your own system resources. Scalability is essential for an efficient smart nudging system, but hardware upgrades are costly. The complexity and size of any system might be hard to predict in advance and leave room for errors in obtaining hardware. For instance, a small local booking system may have difficulty accommodating the increase of new customers after a viral video created a tourism boom. Scalability may be outsourced to a cloud service provider, taking the initial hardware cost. A cloud commonly charges only for resources in use and provides cheaper provisioning of resources for systems of a specific size. For example, small business owners reduce their initial investments in storage and web development resources by using a cloud for their online store. In addition, as hardware get outdated is the cloud responsible for buying new hardware to accommodate customers' demands.

Trusting a service provider to store and process data may be a security risk compared to the edge. In the cloud, it is required to trust the service provider to store and process sensitive data as the cloud is responsible for security mechanisms. Giving up some control to a third party may impose a security risk and seem naive to many users. It can seem gullible to trust big cloud providers with having the users' best interests in mind while also making money. For example, sharing resources may be a security risk when storing data on the same server as other users. The system's software may run parallel to another system, with libraries and dependencies that are not secure. The cloud may pose a security risk relying on the service provider's trust.

Furthermore, clouds are mainly positioned far from the user, which increases latency. Data is usually kept at data centers in remote locations as they demand considerable space to keep all hardware resources. A cloud has high latency as data is sent across large distances between data centers and devices. However, some data might be pre-processed before delivering data to the edge device with the available resources. The cloud can decrease the volume of data needed by performing some system logic at its end. Due to privacy issues, the processing of sensitive data might be vulnerable to attacks in the cloud. Nevertheless, requesting weather forecasts and bus tables is probably not sensitive enough and should be pre-processed in the cloud, to minimize using edge device resources that are not necessary. Pre-processing in the cloud also means sending less data and contributes to decreasing latency.

Cloud supports sharing of data between multiple users. Due to the scalability of resources, a cloud accommodates a growing audience and multiple users. In comparison, edge devices have limited resources and little security, making data sharing unreliable and vulnerable. A cloud can be used as a sharing platform for multiple users who might benefit from the same data. Data from an edge device can be uploaded and shared in the cloud. For example, a user collects data about a hiking route when out walking. Such data may include the GPS location of alternative routes, the weather that day, the time it took to walk, and a picture of the view during the hike. Information from the hike might benefit other users and even motivate them to hike the same route. By sharing information in the cloud can multiple users access it and avoid storing this information exclusively on one user's personal device. Additionally, much data also come from the cloud. For example, bus tables are information that multiple users would need. Minimizing data processing on local edge devices can be done by sharing the fetched data in the cloud. Instead of the several users performing the initial same computational work, the work is performed by the cloud.

Edge computing will provide a smart nudging system with the possibilities of data collection and processing of personal and context-aware data. In contrast, cloud computing may optimize available resources working as an off-loading platform, pre-processing work, and enabling data sharing between users.

5.3.2 Local Server

A local server may be a preferred option to ensure privacy for sensitive data due to storage limitations on edge devices. A server can help limit user access and data exposure by communicating over a local network. However, local servers are often costly and bound to a location.

Limited storage can create challenges for edge computing in large systems with tons of data, as data processing may take a toll on the user experience and the effectiveness of the system. A local server can be responsible for relieving the edge device of some of the processing or storage of data. The communication between the server and device can limit unwanted users' access and data exposure during data transfer. For instance, a local network can consist solely of the device and a server sharing a single limited space. Hence, a local server contributes to privacy of data, which is a requirement for a smart nudging system.

However, the data storage should stay limited to sensitive data as a local server is costly, increase latency, and is inconvenient due to being non-mobile. Firstly, local resources are not scalable on-demand, like in the cloud. Hence, to expand storage means investing in more resources which may be costly. For example, innovations in server technology can require a system hardware update. In addition, data transfer is demanded to move data from the edge device to the server, increasing latency. However, the latency increase should be limited compared to those in the cloud.

A local server is often stationed in one place, making it inconvenient to connect from anywhere. In comparison, a user can access information globally with a cloud as long as there is an internet connection. However, a local server that aims to limit user access and data exposure with a local network would rely on the edge device to connect directly to the server. Then, the edge device would need to be close to the local server. Furthermore, being stationed at one location, the server affects the range an edge device can operate. For example, all workout data from a vacation can fill up the edge device's local storage during a long holiday. As a result, the edge device cannot offload data to the server until it is back home, making edge processing inefficient in the meantime. Therefore, may a local server be best suited for sensitive data storage to limit the data storage and transfer from the edge device. Only historical and sensitive data in the smart nudging system should reside on the local server.

5.3.3 Personalization with IoT

IoT devices conveniently gather specific data about environments or users, contributing to personal and context-aware data collection. However, IoT devices have serious security issues.

IoT devices can assist in a more comprehensive data collection in a smart nudging system due to the variety of IoT devices. For instance, healthcare research suggests the use of digital nudging to improve patient focus, but struggles with the level of variation in diseases, environments, and patients[48]. IoT devices and sensors may provide customization to tailor nudges for individuals and specific environments. For example, multiple motion detection sensors can be placed at the workplace and at home to detect the number of times the user enters a room. With the help of the sensors can the system detect movement in two different environments.

Furthermore, the IoT sensors allow the possibility of gathering data about specific scenarios or variables related to a user's goals or needs. For instance, could the sensor measure the temperature in a car as another sensor detects walking into the bathroom. The sensor data can start the cabin heater in the car based on the second time the user enters the bathroom to brush their teeth if the temperature is below 15 degrees celcius. The range of sensors provides extensive possibilities and combinations to adapt the data collection to a scenario or a district variable. Customised sensors allow for comprehensive data collection analysis in a smart nudging system.

Data transfer from IoT devices to an edge device may leave data vulnerable and exposed. Low-end IoT devices often lack security mechanisms making them easy targets for malicious attacks. For example, the exposure of sensitive and personal information can be achieved through eavesdropping on an IoT network[32]. Bugs or the absence of security mechanisms, such as encryption, make it possible for a hacker to retrieve confidential information during data transfer from an IoT device to an edge device.

However, IoT data may provide useful information which is not considered sensitive. For example, weather data about a specific area might expose the city where the user lives, but may be considered harmless as many citizens live within the same area. Weather data about a location is also of interest to users outside of this location and may not be linked to the user's personal location. Other data, like the user's weight or a grocery shopping list, can be considered more sensitive but may not be an issue for many users. Data sensitivity is very dependent on the user's attitude and whether data can be associated with the user, providing the opportunities for harmful activities if in the wrong hands. Because IoT faces issues with privacy, may IoT devices assist in a smart nudging system by supplementing already collected data from the edge device or focusing on the collection of non-sensitive data.

6

Design of the NuEdge System

This chapter presents the proposed system for this thesis, called NuEdge, an edge-based smart nudging system utilizing edge computing resources for efficient data collection and processing. In combination with IoT and cloud is edge computing used to collect data and construct tailored nudges to a specific user. The design is based on the goal of encouraging users to better their physical health, but can be generalized to fit other scenarios as well.

Section 6.1 gives an architectural overview of the NuEdge system and each component's responsibilities and placement. Section 6.2 then covers the major design choices and expected advantages and disadvantages. Section 6.3 explains the integration between each component and the communication protocols used. Section 6.4 presents data storage management. A data categorization of data storage options is presented to ensure privacy, efficient processing, and data sharing. In the end, section 6.5 covers disregarded requirements, introducing important topics for future work considered outside the scope of this thesis. This includes the complexity of heterogeneity and security.

6.1 NuEdge - An edge-based smart nudging system

NuEdge is a smart nudging system that primarily focuses on providing efficient data collection and processing to construct smart nudges. The system combines edge computing and cloud computing with IoT devices to create a system with efficient data collection of personal and context-aware data, scalable processing and contributes to privacy. A mobile edge device is necessary for the NuEdge system gaining context-awareness and lower latency, while the cloud scalability and off-loading for the edge device. In addition, a local server is also presented as the backup storage for sensitive data due to limited trust in the cloud.

6.1.1 Architectural Overview

To investigate the use of edge computing and the promised benefits, latency, privacy, and context-awareness, a proposed smart nudging system called NuEdge is presented. The NuEdge system architecture depicted in Figure 6.1 consists of an edge device for data collection, construction and delivery of nudges integrated with a cloud for computational off-loading and sharing, while a remote server stores sensitive data. In addition, IoT devices contribute to more personal and context-aware data about specific situations or locations.

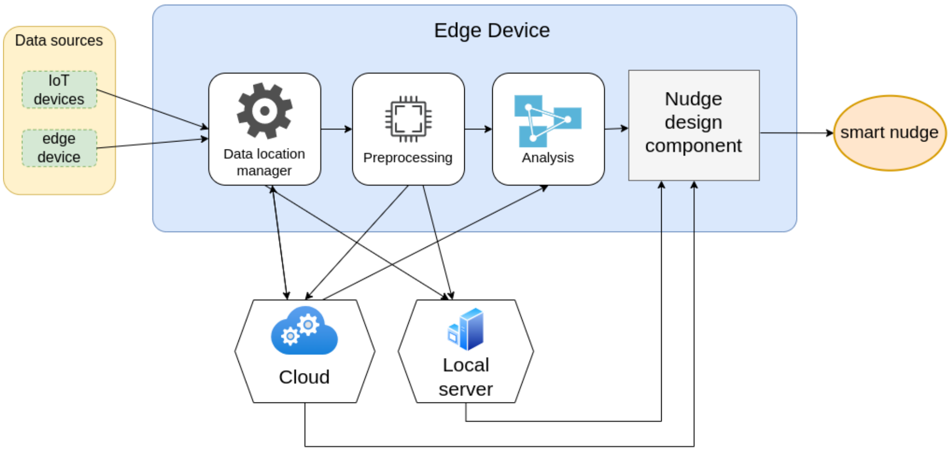

Figure 6.1: A NuEdge system architecture.

The edge device is primarily where the system logic resides. The edge is responsible for data collection, processing and generating tailored nudges delivered to the user, all happening on the edge device. An edge device will collect data through integrating IoT devices and other data sources while also producing data derived from the edge device sensors and from user interaction. All system components are integrated with the edge as it is in charge of control and data management. However, the burden of storage is shared with a cloud and local server.

The cloud acts mainly as storage but can offer computational off-loading when needed. A cloud can be accessed whenever an internet connection is available, offering off-loading for non-sensitive data at non-remote locations. Further, the scalability and availability of the cloud provide possibilities for the sharing of data between users. The cloud may support the edge device in data collection and minor data processing for non-sensitive data, assisting in evaluating the relevance of data collected.

The local server works mainly as a storage space due to the high hardware cost and the inconvenience of moving a stationed server. In addition to the edge device, the server acts as the primary storage for personal and sensitive data, as a local connection is considered more secure than transferring data to the cloud.

6.1.2 Mobile Edge Processing

The NuEdge system is designed to reside on a mobile edge device, like a smartphone. However, the suggested approach is not limited to smartphones but can be generalized to adapt to other mobile edge devices such as IoT devices and smart pads, as they share similar resource capabilities. Nevertheless, due to accessibility worldwide[6] and the extensive interaction between users and phones, smartphones are convenient to use in the NuEdge system. Hence, the primary focus revolves around smartphones and their capabilities, as the edge device, in a NuEdge system.

Smartphone technology has exploded in the past two decades and the market innovations have brought advanced technology into everyday life. As a result, smartphones evolved from suitcase-sized phones to mobile personal computers and media centers where you can call, watch movies, send emails, etc. Modern-day smartphones can conduct computational work previously carried out by a computer due to the innovation in smartphone technology, both hardware and software.

The proximity from a mobile edge device and the collectible data decrease resources used on data transfer. Lower latency is achieved through the convenience of carrying around your device and moving processing closer to the location of data. As smartphones often stay with the user throughout the day, they can provide context-awareness to received data based on the user's location. Smartphones can also be producers of personal data. For example, a step counter application can utilize an existing pedometer in the smartphone, linking the data to the user carrying the device. As consumers become co-producers, data can be produced at the source, leading to limited data transfer. Smartphones provide context-awareness and user-specific data to the NuEdge system, with a limited need for data transfer enabling more efficient processing.

Other edge device alternatives include embedded systems, like IoT devices and sensors. IoT devices, the producer of data used in a nudge, yield lower latency and propose more efficient processing. However, embedded systems have limited resources and often lack complex operating systems to perform system logic and computational work. Other alternatives are often servers or bigger computer structures providing enough resources for any resource-intensive work, but often expensive and non-mobile. For example, servers might require a permanent position and are costly to invest in and replace. In addition, the positioning of such servers needs to be close to the user to limit the data transfer, and thus can not provide the same convenience as wearable edge devices.

6.2 Design choices in the NuEdge System

The NuEdge system consists of an edge device integrated with a cloud, local server, and IoT devices to collect, process and construct tailored nudges. First, the edge device contributes to vast data collection and processing of personal and context-aware data to construct the nudges efficiently. A cloud offers scalability and data sharing with other users in the system, while the local server is the backup storage of sensitive data. Lastly, IoT devices can collect data about different specific variables and environments, contributing to a more comprehensive analysis of the user and nudge.

6.2.1 Edge computing

Edge computing can provide vast data collection, lower latency and contributes to privacy by utilizing resources closer to the edge of the network.

First of all, a mobile edge device can collect data from multiple environments as the user change location. The mobility of the device is convenient to monitor the user throughout the day, providing context-awareness to the collected data.

Further, can personal data be generated by the sensors and usage data on a personal edge device. However, users will expect privacy when personal information is stored and processed on the edge device.

Privacy is highly important as lost personal data can have major consequences for both users and society. Edge computing limits data transfer by being the primary data collector and processor. Privacy is kept as sensitive data can be stored on the edge device, which only the user can access. However, the edge device is still vulnerable if the edge is stolen or lost.

Lastly, edge computing in a smart nudging system provides lower latency and utilization of device resources. Edge computing limits the time to process data that can ensure the delivery of nudges quickly. The need for faster processing is further emphasized by the vast amount of data collected in the NuEdge system. Additionally, edge computing resources have improved over the years and have often unused potential. By utilzing these new resources the workload may be distribute more evenly within the network.

However, edge device resources like power consumption and storage may be limitations in a smart nudging system with multiple users and storing data over a significant period. Therefore, additional resources are provided in the NuEdge system to accommodate an expanding smart nudging system over time.

6.2.2 Cloud computing

While the edge is the central place for processing due to the closeness to data, can the cloud assist as an off-loading platform. Large amounts of data may strain the edge device resources and decrease the user experience. For example, an application running in the background may drain battery life by collecting data from IoT devices during the day. To obtain a good user experience, less sensitive and time-sensitive work is outsourced to the cloud.

Scalable resources allow the cloud to handle vast amounts of data in terms of processing power and storage at a fair price. The convenience of dynamic storage without an initial costly investment on hardware makes the cloud, in general, a cost-efficient option. However, uploading and downloading data to the cloud has a very high data transfer cost. Therefore, the edge is a more efficient way to meet processing requirements for the NuEdge system. The edge device efficiently processes nudge data, while the cloud can process and store less time-sensitive data with scalable resources.

Secondly, the cloud is the optimal option for sharing content with other users.

A cloud can easily share data with data centers worldwide and has enough resources for any size system. Compared to a cloud that can accommodate a significant number of users, the edge device is limited by its resources. For example, an edge device has limited storage capabilities because the physical size of the device. Shareable data require a significant database to store data from multiple users. Sharing data can be beneficial in a smart nudging system, in terms of learning about similar users and the effectiveness of nudges. However, sharing data in the cloud creates privacy issues, limiting what data to share.

6.2.3 Local storage

The benefit of the local server is off-loading sensitive data when the edge has limited storage capacity and providing a level of privacy the cloud can not be trusted with.

A local server only accessible by the user provides backup storage for sensitive data. The NuEdge system deals with privacy on the edge device but may strain its storage capabilities. Therefore, the system includes a local server to store and process data to limit the pressure on edge device resources for sensitive data. Some data may not be required immediately and, therefore, held by the local server instead of the edge device. However, due to the cost of hardware and the efficiency promised by the edge, most computational work remain to be performed by the edge device. A local server offers stable storage to the NuEdge system with more storage capabilities than the edge.

6.2.4 IoT devices

IoT devices contribute with context-aware data about specific variables and environments. Low-cost components and sensors can be customized to detect and monitor particular scenarios or variables for a user. For example, one IoT sensor can register heart rate during a hike, measuring the intensity of the activity. IoT devices provide the NuEdge system with relevant and sometimes live data about the user's environment. However, IoT devices have limited security mechanisms and might compromise privacy by collecting personal data. Fortunately, sensors are often not linked to a specific user identity, but rather the edge device is responsible for adding context to the collected data when processed.

6.3 NuEdge Integration

Figure 6.2 presents the integration between all components and devices in the NuEdge system. The mobile edge device, like a smartphone, is the main component responsible for data processing and the construction of nudges. All other components such as the cloud, local server and IoT device are integrated and connected through the edge device.

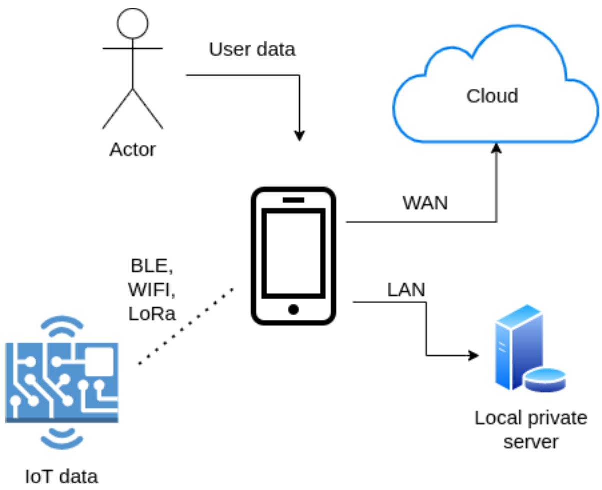

Figure 6.2: The NuEdge integration setup.

The edge device can produce personal and context-aware data from sensors and user interaction. For instance, the mobile edge device inhabits sensors that can measure step count or heart rate to determine the physical shape of the user. In addition, sensor data can further contribute to context-awareness with data retrieved from other sources. For example, an IoT temperature sensor might output the number of degrees, while the edge device provides context to the location where the temperature was collected. Furthermore, user interaction with the edge device may give insight into the user's habits and be valuable information to construct tailored nudges. For example, lack of interaction over long periods suggests sleep or work. Hence, it is not a great time to nudge the user as they won't necessarily see the nudge when intended.

Sensor data not produced by the edge device can be collected from IoT devices over a wireless connection. Standard options include Wi-Fi, Bluetooth (BLE) and LoRa (Long Range). Some things to consider in the choice of wireless technology are communication range, power consumption, data throughput and latency[1]. In general, Wi-Fi or Bluetooth are used for lots of wireless smart objects and is preferred as a result of their already well-established infrastructure and documentation.

However, expanding the NuEdge system might demand multiple IoT devices to stay connected simultaneously, hence other technologies offer a better fit. Different wireless technologies accommodate a variety of robustness, price, range, and setup needs. For example, if the edge device monitors weather forecasts on top of a mountain, LoRa provides greater coverage than Wi-Fi or Bluetooth. More complex systems might demand a more permanent setup, which an organization or government might maintain, and therefore use cellular network connections like 4G or even G5, although costly.

Collected data can be transferred to the cloud, local server or on the edge device for data storage. The cloud connects to the edge device over a wide area network (WAN). WAN connections are required as a cloud is often stationed far away in data centers. For example, the distance from Tromsø to the nearest location of an Azure data center[2] is 1700 kilometers away in Oslo. With WAN, the system accommodates data transfer over large distances and can enable the sharing of data with others connected to the network.

The local server is connected to the edge device over a local area network (LAN) to limit unwanted user access and malicious cyber activity. The characteristics of a LAN are a connection of devices within a single, limited space[3]. A LAN ensures privacy and the protection of data as the user has control of the network, and can limit access to other users. The NuEdge system benefits from the privacy of the LAN, but with the convenience of a wireless connection.

6.4 Data Storage Management

Data analysis and processing help determine the relevance of data in a nudge and establish the most suitable storage location. Before data can be used in a nudge, data is processed and analyzed to filter out irrelevant information. Furthermore, the sorted data is categorized according to the most suitable storage and processing location. Sensitivity, sharing, and size are three major properties to describe different purposes of collected data in the NuEdge system. Data categorization gives insight into how and where data processing and

1. https://blues.io/blog/network-connectivity/
2. https://azure.microsoft.com/en-us/
3. https://www.cisco.com/c/en/us/products/switches/what-is-a-lan-local-area-network.html

storage should happen. It helps determine storage location and the relevance of data within the NuEdge system.

6.4.1 Data Categorization

One major challenge with the NuEdge system is the management of heterogeneous components within one single system. Multiple components need to interact differently, requiring the NuEdge system to accommodate different communication protocols and interactions. Data is categorized based on key properties to determine where the data should be stored and processed, either the edge, cloud or local server in the NuEdge system. The three crucial properties; sensitivity, sharing and size, are considered important indicators to differentiate between data storage and processing needs.

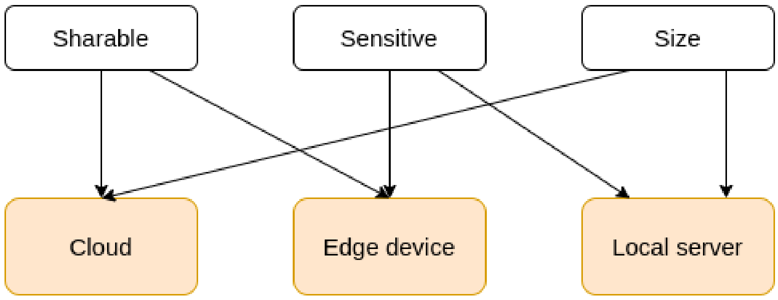

Figure 6.3: Categorization of data storage in NuEdge.

In Figure 6.3 are all the possible storage locations presented with their main properties in regards to storage and computational power. Arrows point to the appropriate storage location in the NuEdge system in regards to the properties from which the arrow is connected. The three main places to keep and process data in the NuEdge system are on the edge device, like a phone or tablet, a local server controlled and managed by the user, and the cloud, a third-party service provider. Additionally, IoT devices provide options for storage and processing, but are considered very limited in computational power and security. Hence, the NuEdge system will not rely on the storage and processing capabilities of IoT devices.

6.4.2 Sensitive Data

Firstly, sensitivity is important to users to ensure privacy and data protection. Malicious cyber-attacks are interested in sensitive and personal data to bring suffering to users or for financial gains. The social and economic repercussions of the misuse of sensitive data are potentially huge, negatively affecting both users and society. The NuEdge system stores sensitive data on the user device or local server to limit data transfer and user access.

Both local server and edge devices are components operated by the user, contributing to privacy as the user is in change of access to the data. Additionally, edge devices benefit from the proximity to data, providing minimized data transfer. The edge device is the main data collector and producer and, therefore, may eliminate most data transfers. Transferring over a network exposes data and yields opportunities for data interception. However, a local server can minimize data exposure with a local network, solely transferring data between the source and the local server.

The cloud is an unsuitable storage location for sensitive data as access to the cloud requires data transfer over wireless networks. Hence, it runs a risk of unauthorized access when offloading to the cloud[49]. As data centers are often far away, data latency and exposure time also increase.

Another significant issue is trusting a service provider, leaving the control and responsibility with a third-party organization. Although not a security issue, it would be naive not to consider the potential problems of giving up control to someone else. For instance, how will a service provider prioritize your resources during downtime or in case of hacking? Trust between the service provider and customer is essential to consider.

Furthermore, virtualization techniques applied in a cloud create challenges such as unauthorized access and VM to VM attacks[49]. A VM, short for virtual machine, is a physical computer assessed from a virtual connection. Clients of a service provider often share VMs but allocate separate parts of the VM. However, untrusted clients may take control of the shared resources on a VM through hacking. Sharing of hardware means trusting other clients as well as the service provider. Therefore, it is only the edge and a local server that is regarded as safe spaces for storing sensitive data.

6.4.3 Shareable Data

Complex analysis and exchange of information are possible with sharing of data. Sharing, in this context, means data that is kept in storage but is available for other users and systems. Sharing data allows users to learn from the others' experiences and provide insight into different users of a system during with data analysis.

The cloud is a great place to store shareable data as it is global and scalable. Uploaded data to the cloud can be accessed efficiently worldwide due to the extensive coverage provided by cloud service providers, such as Microsoft Azure, Amazon AWS, and Google Cloud. The scalability offered by the cloud also makes sharing preferable here, having the opportunity to expand data storage resources as needed.

Additionally, the edge device can share data efficiently with nearby users. By obtaining a connection with a specific user, either wired or wireless, can the edge device transfer data directly to another specific user. It is preferable to use the edge device for sharing sensitive data as you can control the connection better than with the cloud. Further, the mobile edge device can transmit data without an internet connection. The edge device can share data using other communication protocols, such as BLE, compared to the cloud. However, the edge device's coverage and simultaneously sharing with multiple users may be limited. Storage capabilities on an edge device may be unable to host an extensive amount of shareable data from itself and other users. As a result, the edge device may share specific and sensitive data to a few users, while the cloud can reach many users.

The local server is solely meant as sensitive data storage and is not considered a good option for sharing of data. A user would have to be near the server's location to gain access, making connections inconvenient. Additionally, limited user access to the local server due to protecting sensitive data makes the local server inadequate for storing shareable data, which multiple users should have access to.

6.4.4 Size of Data

Lastly, the size of data or computational workload is relevant to considering storage and processing location. In the NuEdge system, it is assumed that data may requiring a substantial amount of computational storage or work. Therefore, significant size data would be best stored and processed at the cloud or local server due to resources limitations such as storage and computational power of an edge device.

In general, the cloud and local server have more resource capabilities than a mobile edge device. Hence, they can perform computations efficiently and store more significant amounts of data than the edge device. However, this only accounts for work of a specific size. The proximity to data on an edge device means faster processing and lower latency. Data transfer to the cloud or server increase latency, but for more significant-sized data, the mobile edge device can outsource the workload when needed. For example, the edge device might outsource workloads that strain resource capabilities and affect the user experience. The local server is the preferred option for storing and processing sensitive data. In contrast, the cloud may benefit from scalable resources, tackling almost any amount of data storage and computational work. However, at the cost of latency and money.

6.5 Disregarded requirements

Heterogeneity and security are requirements that should be considered in a smart nudging system design. However, due to time limitations and complexity, have these topics been disregarded. Nevertheless, these are topics of great importance and considered valuable to mention, informing about future work and possible complications for a smart nudging system.

6.5.1 Heterogeneity

Heterogeneity is a very complex challenge, often present in distributed systems[50]. Some aspects of the topic will be discussed as part of the evaluation, while the challenges related to the actual implementation of such a system are left out of the scope of this thesis. Therefore, the NuEdge system is not designed for seamless joining and connecting to new devices or sensors. The sources responsible for incoming data need to be integrated beforehand to handle their communication requirements. Ideally, the system can create more generalized communication protocols to limit cross-over overhead[51]. Issues related to heterogeneity revolve around integrating heterogeneous sources, devices, data, interfaces, etc., with limited complexity. Designing tools, interfaces, algorithms and mapping strategies[51] to handle heterogeneity may contribute to tackling the issues.

6.5.2 Security

Providing safe solutions to users which protect their data and avoid the misuse of the intended system is of great importance. Malicious cyber activities are estimated to cause damages of up to 6 trillion dollars in 2021 alone, with an expected increase over the next five years[4]. With personal user information present in the NuEdge system, security measures should be taken to ensure the safety of the data and to avoid malicious cyber activities. Common threats to be aware of, especially in edge and cloud computing systems, include virtual machine attacks, eavesdropping, jamming, denial of service, session hijacking, and man in the middle attacks[52]. The NuEdge system acknowledges these threats but focuses primarily on privacy through limited data transfer of sensitive data. Sensitive data is never shared over an open internet connection, but nothing extra is implemented or designed to ensure security in all locations. Standard security mechanisms like data encryption, authentication schemes and logging should be considered when designing a smart nudging system in the future.

4. https://cybersecurityventures.com/cybercrime-damages-6-trillion-by-2021/

7

Implementation

This chapter presents an implementation of a NuEdge system. A prototype has been developed as a proof-of-concept to explore the possibilities and opportunities of edge computing in a smart nudge scenario. The prototype consists of a cloud and IoT device integrated with an edge device, whose primary goal is to nudge users to achieve better physical health through more physical activity.

Firstly, section 7.1 presents assumptions and specifications to clarify the limitations and requirements of the implementation. Section 7.2 is the application explained from the user's point of view. Features are presented, and their primary purpose is explained. Section 7.3 presents the system overview of the implementation as a whole, explaining each component and its areas of responsibility. Lastly, section 7.4 examines each component further by explaining their data handling and integration with one another.

7.1 NuEdge System Prototype

The assumptions and specifications of the system are presented before introducing the application. Assumptions help clarify the application's limitations. The specifications narrows the scope of the implementation and point out requirements that should be in place for a successful NuEdge application.

7.1.1 Assumptions

Before presenting the programmable implementation of the NuEdge system, certain assumptions are made about the system's environment, such as data formats, user interaction, and third-party service providers. Assumptions should help clarify and define the scope of the implementation. Assumptions may also be a disclaimer to introduce mechanisms that should be in place for a successful NuEdge system, but which may be outside the scope of this implementation. The importance of this prototype is not to define and construct real-world nudges for a user, but rather to present a possible implementation of an edge-based smart nudging system. The assumptions are:

- **The nudging goal, user profile and suggested activities are known.** This indicates that all information which is to be collected by the NuEdge system is considered somewhat relevant in regards to the nudge goal.

- **Data is safe when in storage.** Data stored anywhere should be considered safe, available and not lost when placed in storage.

- **Data is always available to construct nudges.**The system will always have some data to work with in constructing a nudge. This ensure that the system will always try to create nudges, even though data sources are unavailable or not responding.

- **Data collected is continuous and provides the expected information.** Ideally should the system be able to detect false, corrupted or deviated data and respond to it. However, it is assumed that the data retrieved from the data sources are the expected information without extensive time delay.

- **Available resources when processing on the edge device are exclusively its own.**Computations preformed on the edge device is only on the edge device and can not be outsourced to keep privacy a priority.

- **A local server offers a similar setup to a cloud, but is limited in it's variety of services.** The unavailability of a local network and router needed for a local server setup limits the implementation to consist of a cloud, IoT, and edge device. The cloud integration provides insights into the similar setup of a local server. However, the local server would have far fewer services and computational power available.

7.1.2 Specifications

Listed below are the main specifications for the system implementation, based on the NuEdge system design. The specifications present the minimum requirements to be expected by the implementation as a edge-based smart nudging system.

- Users should receive tailored nudges at appropriate times
- Nudges should be constructed on the edge device based on collected data
- Sensitive data should primarily be put into a safe storage space on the edge device or local server
- The user can chose to share data which is then uploaded to the cloud
- The user can retrieve shareable data from the cloud
- The edge device receives sensor data from an IoT device

7.2 Application Overview

The NuEdge system is implemented on the edge device as an application called Nudge Me To Walk(NMTW). The application acts both as the front-end and back-end of the system responsible for constructing and delivering nudges to the user. The front-end consists of a home screen with a step counter, a settings page for adjusting step goals, and a walk view to track and share walking data with other users.

The goal of the application is to motivate the user to walk more by displaying and sending notifications based on retrieved data, such as step count, location, and inactivity detection. Nudges are delivered as notifications on the user's edge device triggered by limited physical activity within a given time frame or location. For example, if the application detects only 500 steps before lunchtime, should the user be nudged to take a short walk to get some water or walk around the building. Alternatively, if a user is close to a supermarket after work, may a nudge suggest walking to get dinner on the way home. In addition, the application provides a simple setting view for adjusting the daily step goal for a user. Daily steps indicate the user's fitness level or ambitions, helping construct nudges accordingly.

Firstly, the home screen Figure 7.1 presents the user with a progress bar and a motivational text based on their current physical activity. The progress bar shows the number of total steps against their daily step goal. This is the main indication for the user of their current progress and daily physical health. In addition to the progress bar, there is also a short motivational text as a nudge. For example, the text may inform the user of the number of steps left to reach a goal, how many steps to a specific place, or facts about other people's walking habits or research.

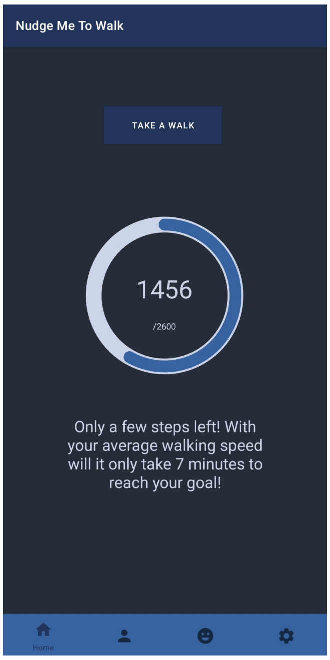

Figure 7.1: The NMTW home page.

From the home view in Figure 7.1, can the user choose to track a walk independently. An independent walk is any walk or hike initiated by the user, tracking the number of steps within a time frame chosen by the user. It differs from the daily step counter as it needs to be started and stopped to register the data as an independent walk. For example, while the step counter detects all steps within 24hours, may an independent walk measure the number of steps for 45 minutes as the user walks around the local park.

Tracking specific walks or hikes may encourage users to walk more and not just reach their daily step goal. While the step goal should encourage consistent daily walking, may the tracking of independent walks offer an incentive to make an extra effort. The independent walk page seen in Figure 7.2 encourages users to track walks independently and share their experiences with other users. Sharing data with others might motivate and encourage users with similar goals.

Tracking intentional walks initialized by the user can give insight into the user profile and construction of nudges. Information such as the length of their walk, the amount of time they think a walk takes, or the locations the user considered preferable for walking provides valuable insight to the system. For instance, may a user's average walking speed for a specific hike deviate from the general group of users with the same daily step goal. The information indicates either that the daily nudge goal is too ambitious or that the user has a greater potential. Hence, nudges should push the user towards walking more or provide research to recommend a daily step goal based on similar users.

While walking, the user is given the opportunity to take a photo, bringing context to the activity. For example, a hike may motivate a user more when seeing another user's photo of a beautiful sunset during a walk at the beach. The walk is no longer just the number of steps or a location, but the photo provides information about the surroundings and terrain of a hike. A walk consisting of step data and an image, may be uploaded to the cloud only with the user's consent because of privacy.

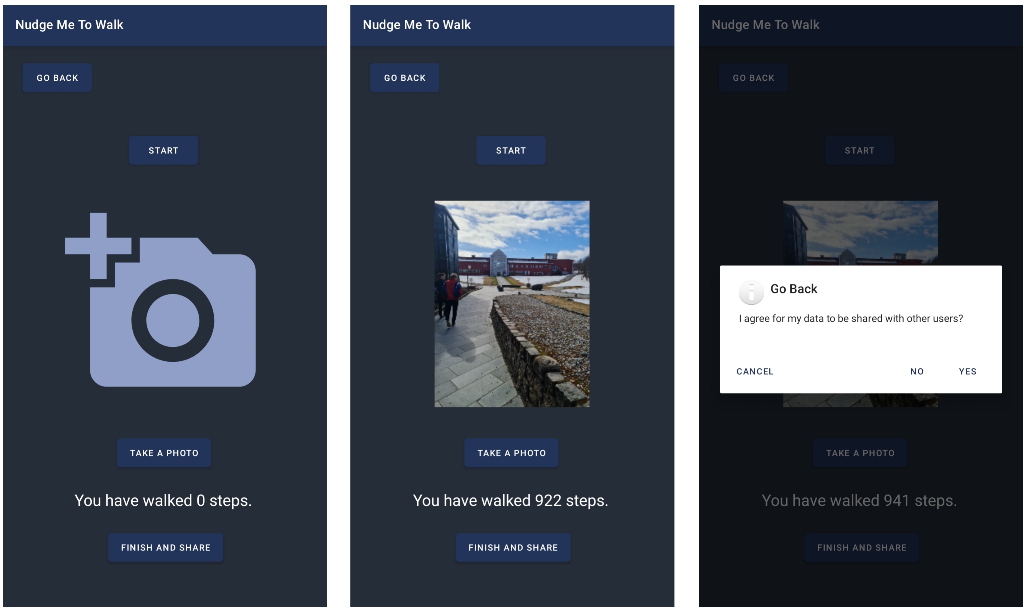

Figure 7.2: The NMTW application views for tracking of independent walks.

7.3 System Overview

The prototype of the NuEdge system is an android application running on a Samsung smartphone integrated with an Azure cloud and an esp32 micro controller, as the IoT device. A system overview can be seen in Figure 7.3. The main logic of the system resides on the edge device, being both the constructor and deliverer of nudges. The edge device is integrated with an Azure cloud primarily as storage for shareable data from independent walks. The IoT device is limited to data collection only, delivering data to the edge device over BLE. Data collection from the IoT device consists of inactivity detection at work for a specific user. The prototype collects shareable walking data via Azure cloud, steps and location from the edge device, and inactivity data from an IoT device at the office. These data sources are used to construct nudges to enhance the user's frequency of physical activity.

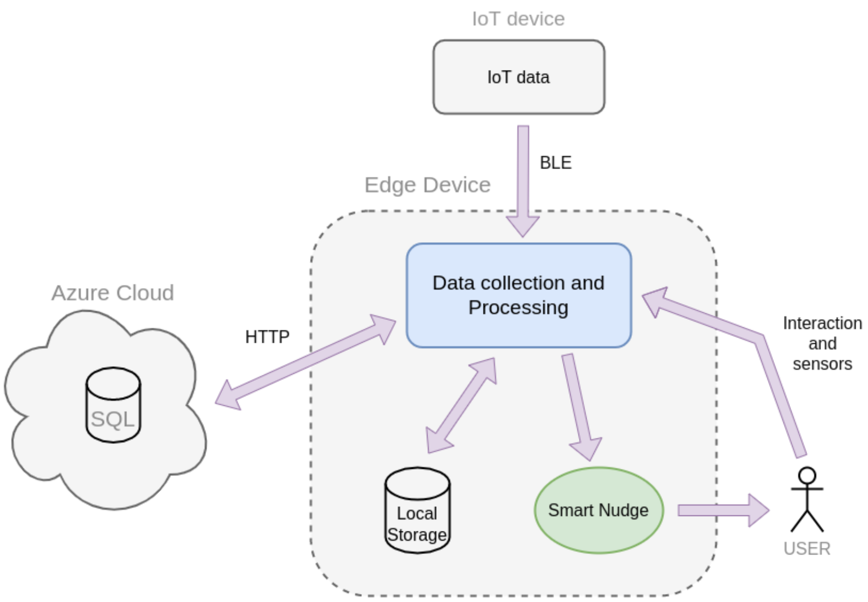

Figure 7.3: System overview of the implementation.

The edge device, a Galaxy Note20 5G, is the primary data collection and processing component. The edge device is responsible for collecting data, processing the data, and constructing and delivering nudges to the user. All other devices are connected to the edge device. Once data is collected either from sensors on the edge device or IoT device, is it processed to determine the relevance of the data. Data is either processed and used in a nudge right away or stored either in the edge device database or cloud database.

An Azure cloud connects to the edge device over any internet connection, Wi-Fi, or cellular. The cloud consists of a SQL server with a SQL database and functions app[1]. The SQL database contains records of steps from the walking trips the user wants to share with others. The database is accessed through an API provided by a functions app written in Python. Function apps are code snippets triggered by events running as serverless Azure service apps.

The IoT device, an esp32 pro(the green square in Figure 7.4), connects to the edge device over BLE. The esp32 is a micro controller responsible for communicating and transferring data from the sensor to the edge. A photo diode(the blue circle in Figure 7.4), a sensor for detecting light, is integrated with the esp32 to register the amount of light received. Based on the amount of light received by the photo diode, the esp32 returns a binary value to the edge device. In the implementation, the sensor is placed on the user's chair. If the user sits down, the photo diode will be covered, and the sensor should detect little or no light. On the other hand, when an abundance of light is detected, it indicates that the user is not sitting. However, the edge device should only receive data after the user is detected at a workplace location or within work hours during weekdays.

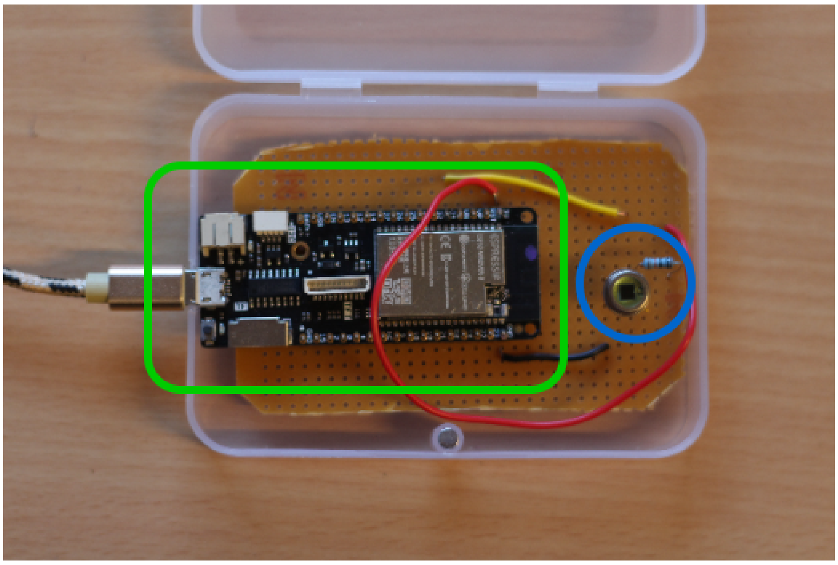

Figure 7.4: The IoT device for sitting detection.

1. https://docs.microsoft.com/en-us/azure/azure-functions/functions-overview

7.4 Data Integration and Handling Approaches

The edge device integrates and handles data, distributing the workload and storage between itself and the cloud. The edge device can send and receive data from the cloud through APIs. To limit strain on edge resources work API calls performed as background work during times of low-activity. The IoT device provides data, with the edge device acting as a BLE client to retrieve the data. Call operations to the BLE server also run as background work and should limited to weekdays between work hours.

7.4.1 Edge device integration and data handling

A Galaxy Note20 is the edge device connected to all other components through wireless connections. Wireless connections ensure the edge device's mobility and convenience as users change environments. All data collected from different sources is processed on the edge device to determine their use in a nudge and storage location.

Whenever the edge device has access to the internet, either over Wi-Fi or cellular can the edge device connect to the Azure cloud. Data is processed in the background by a background manager to limit poor user experience. A background manager limits processing on the main thread as it may lead to poor performance, staling, and unresponsiveness on the edge device[2]. Further, to save edge device resources for the most important tasks and maintain a good user experience, data is scheduled when the smartphone is idle or in periods of inactivity from the user engaging with the device.

The edge device auto-connect with the IoT device after the first pairing performed by the user. The paired BLE device will send data every 10 seconds, reporting on the last five registered values from the sensor. The edge device will only connect when in proximity to the IoT device. IoT data is processed and used in analysis to determine if the user is sitting right away, without the need for storage as the data is time-sensitive.

Step counter data from the edge device is processed as background work and a time triggered analysis determine when to nudge. An analysis determine if the user is close to their goal, and nudge the user accordingly. The data is used

2. https://developer.android.com/guide/background

to calculate the amount of steps left, informing the user of how far away from the goal they are. A the end of the day is the total amount of steps sent to the cloud for storage. This historical data may be useful later to perform more empirical analysis on the improvements made by the user.

7.4.2 Cloud API

The cloud assists the edge device in storing walking data, especially data the user allows to be shared with others. For example, with logging an independent walk, the user can share the number of steps potentially together with a location or even images. Furthermore, by sharing data made available in the cloud, the user should also be able to gather data in the future from other users. Data from other users may assist analysis and help to construct nudges based on similar users' experiences. For example, nudges may suggest walking based on the average time spent walking every day by users with a similar daily step goal.

The sharing of data is available by an API call to the cloud for inserting steps into the SQL database. An Azure function app, a serverless Azure service, allows the system to run event-triggered scripts of code without infrastructure management. A function app provides the API for inserting steps to the walk database and fetching the total number of steps from independent walks.

7.4.3 IoT workflow

The smartphone and esp32 are connected over Bluetooth. The esp32 acts as a BLE server, while the edge device can be connected to the server as a BLE client. The BLE server provides a service with one characteristic UUID, an unique id to identify and receive BLE data, which the BLE client can read. The characteristic keep a boolean value indicating if the user is sitting or not. The boolean value is based on the input from the photo diode. The photo diode output a value between 0 and 700 depending on the amount of light observed. Results from trying to cover up the sensor show that values above 472 provide enough light to indicate that the user is not sitting down on the sensor.

The system wishes to nudge the user if sitting exceeds 1 hour without movement with short breaks, such as bathroom breaks and coffee breaks included. To ensure consistency and limit errors sitting values are requested multiple times in a row. These values are then analyzed, which concludes if the person is most likely sitting down or not, based on the majority of true or false. The edge device performs all esp32 BLE connections as background work with a work manager scheduled to perform work when the user is not using the device actively.

8

Evaluation

This chapter evaluate the role of edge computing in smart nudging. Combining existing research on edge computing with implementing a NuEdge system, the prototype has investigated the possibilities and limitations of edge computing in a smart nudging system.

Firstly, section 8.1 focuses on the implemented NuEdge system prototype. Key observations from the implementation include edge device processing and data collection, integrating components and communication protocols. Section 8.2 extends the discussion to the general design of a NuEdge system. The proposed integrations and components are evaluated without a specific scenario in mind. The evaluation includes how well the requirements was fulfilled and cloud security. Further, section 8.3 considers the general use of edge computing in smart nudging. Observations from the implementation and the research on edge computing are combined to provide insight into the possibilities and limitations edge computing poses in a smart nudging system. Future work for the implementation and edge computing in smart nudging is suggested. Lastly, section 8.4 summaries the main takeaways from the evaluation.

8.1 Observations From the Implementation

The Nudge Me To Walk(NMTW) application provides an example of the NuEdge system applied to a real-life scenario, such as that of improving physical activity.

This section introduces the observations and insights gained from the implementation. The main observations including data collection and processing, different communication protocols and cloud integration.

8.1.1 Data Collection and Processing

Observations from the implementation showed that the edge device can collect, process, and deliver a nudge to the user successful. However, the implementation is limited to a single edge device. Therefore, should the system be implemented in a larger scale to confirm the contributions of edge computing in a smart nudging system.

Data was successfully collected from both the edge device sensors and IoT device's sitting sensor. The collected data was then analyzed to determine their relevance and storage location. The IoT data was processed right away on the edge device to verify if the user was sitting or not. The results from the sitting detection nudged the user if inactive for an extended period. Sitting data was not saved on the edge device, as it was time-sensitive and only relevant right away.

Step data from the edge device would stay in the local storage of the device before being sent to the cloud for long-time storage. The data was used to calculate how close the user was to their step goal. Based on how many steps they needed to reach their goal, a nudge was constructed accordingly to the current amount of steps. Before the next day, would the total steps of that data be uploaded to a database in the cloud. The data could later be used in progress reports or more complex analyses to identify patterns. Independent walk data was similar to the step data, uploading data to a database for independent walking trips in the cloud. Independent walk data was also saved for later analysis as historic data.

The edge processing successfully run computational tasks in the background, processing and collecting data while the user was interacting with the edge device. No observations of latency issues or staling when running the application in the background while performing other application activities simultaneously. However, it was to be expected with the limited amount of processing and data collected in the implementation.

8.1.2 Wi-Fi vs. BLE

BLE and Wi-Fi are the chosen communication protocols responsible for data transfer in the NuEdge system. Both are widely used in wireless communication between devices having already well-established infrastructure, but both technologies have their own area of expertise. While Wi-Fi offers a longer range and lower latency for data transfer, BLE is more energy-efficient and accurate in determining location. The following evaluation revolves around what areas each communication protocol is best suited for regarding the implementation. Wi-Fi was initially responsible for the communication between the IoT device and edge device in the prototype. However, BLE was chosen to be the most convenient in the prototype due to allowing for multiple simultaneous connections without optimizations or scheduling between devices.

In Table 8.1 are some common characteristics for wireless communications presented, comparing BLE and Wi-Fi capabilities[1][2][3]. However, certain characteristics are more important than others for a smart nudging system. For instance, compatibility with multiple resources is more critical than complete location accuracy. Using the same technology with multiple devices contributes to better data management of heterogeneous resources, which might be more important than the exact location. For example, an accuracy deviation of 5 meters would not necessarily raise a problem if the goal is to measure an area over many kilometers. Therefore, in the NuEdge system may both BLE and Wi-Fi be good options for different scenarios.

	Wi-Fi	**BLE**
Range	Long range	Shorter range
Latency	Low for larger files	Low for small transmission rates
Bandwidth	High bandwidth	BLE meshing may allow for greater transmission rates
Accuracy	Less accurate indoors	More accurate, but less range
Compatibility	Can be detected by devices with WLAN enabled	Can detect BLE signals on Bluetooth enabled electronics
Data Privacy	Public Wi-Fis are vulnerable to unwanted data exchange	Peer-to-peer network connection contributes to privacy
Power consumption	High consumption due to bandwidth and range	Energy-efficient with low transmission rates

Table 8.1: Comparison of Wi-Fi vs. BLE capabilities.

1. https://askanydifference.com/difference-between-wifi-and-bluetooth-with-table/
2. https://www.cabotsolutions.com/ble-vs-wi-fi-which-is-better-for-iot-product-development
3. https://app.ioterra.com/articles/ble-vs-wi-fi-which-is-better-for-iot-product-development-ifrmfwltvg16

The wireless connection between edge and cloud is Wi-Fi due to the existing infrastructure and communication over the internet. Therefore Wi-Fi was also first chosen for the communication between IoT devices and edge. With Wi-Fi support, the IoT device could be set up as a simple web server, connecting directly to the internet. BLE does not provide IP support and cannot connect directly to the internet, but rather have to use another device as a gateway.

The esp32 micro controller communicated first with the edge device over Wi-Fi due to the simple web server setup and broader bandwidth. However, discoveries from implementing the prototype suggested that a Wi-Fi connection is limited to a single device. Meaning the user would be unable to connect to the internet while retrieving data from the IoT device. With an edge device that the user uses for everything from checking the news to scrolling social media, it may limit the user experience to only allow one Wi-Fi connection at a time. For example, if the esp32 occupied the Wi-Fi connection from 8 am to 4 pm as it was checking if the user was sitting down, the user may not be able to check the weather, news, or social media in the meantime. The inability to simultaneously have more than one Wi-Fi connection affects the user experience and gives the user an incentive to turn off data collection from the IoT device. Therefore, BLE was implemented instead, as it allows for multiple simultaneous connections without occupying the Wi-Fi connection needed for internet activities.

Other options would be to get more Wi-Fi adapters to allow for multiple connections or optimize switching between connections through a scheduling algorithm. For example, priority scheduling could prioritize the user's internet connection over IoT data collection. The system would only allow the IoT device to connect when the user is not on the internet or during times of inactivity. The user experience would be intact, but data from the IoT device to the edge device would be insufficient. Therefore, since BLE does not require additional optimizations or adapters to allow for multiple connections, it is the most convenient choice for IoT communication.

8.1.3 Cloud integration

The integration of the cloud provided insight into the extensive services offered by the cloud, like serverless functions and SQL. However, it also introduced issues of navigating cloud resources and services.

The implementation was a cloud populated with a SQL server holding the SQL database for walking trips. With the help of Azure functions, getting data to and from the edge device was done using an API. Utilizing Azure functions simplified and abstracted away some system logic provided by the Azure function service. Additionally, function app are serverless, meaning the cloud provider is responsible for running the software and maintaining hardware resources. Azure functions proved to simplify and maintain the database for walking trips in the implementation. However, the Azure cloud platform provides multiple services to accommodate different system requirements.

Observation from using the Azure platform is the significant amount of services available to the user. Hence, Azure can provide scalability and convenience as the platform can accommodate different needs with different services. For instance, the security mechanisms offered in the cloud seem to outweigh the cost and time it could take an independent server owner to implement and maintain it on their server. It would seem fair to assume that prominent cloud providers, such as Azure, may accommodate security needs better than individuals or small businesses. Cloud providers has developed their services over multiple years using software engineering and running services on the newest available hardware.

However, the extensive services available can make it inconvenient to choose and navigate between services. Experiences from using the Azure cloud showed the challenges of making a valid decision on what services best fit an application. Further, the cost may be an initial variable for choosing cloud services, but if one does not pay attention to billing or settings, one might be misled to pay for more than necessities. Nevertheless, like any new skill, one must investigate what cloud services would be the best for a system or application.

8.2 Analysis of the NuEdge System Design

This section evaluates the proposed system design, NuEdge, as a smart nudging system architecture. Firstly, a short evaluation of the system requirements and if they have been fulfilled will be presented. Next is evaluating the original design choices of having a local server for sensitive storage. Design choices of the NuEdge system are already explained in chapter 6; however, after implementing the system prototype, certain discoveries created a discussion about the need for a local server. Evaluation of the original design may suggest replacing a local server with the cloud for sensitive data storage. Lastly, the cloud's significant amount of services and resources may outweigh the issue of trusting a third-party service provider.

8.2.1 System Requirements

The proposed system, NuEdge, aims to satisfy the main requirements identified for a successful smart nudging system. Nevertheless, due to time limitations, the primary focus has been on ensuring efficient processing and personal and context-aware data collection promised by edge computing. In addition, measurements to contribute to privacy have also been taken into the NuEdge system design, but only to a limited degree, acknowledging the potential of security issues for the smart nudging system.

The evaluation for each requirement is:

Personal data and Context-awareness - The NuEdge system provides personal and context-aware data collection through the edge device. Furthermore, is the edge device a personal mobile smartphone following the user around. Smartphones tend to stay with the user throughout the day, providing valuable insight into the user and its environment at specific times. The smartphone also has multiple sensors and can contribute to collecting personal data for a single user.

Furthermore, the inclusion of IoT devices integrated with a mobile edge device can add to personal data collection and monitoring of specific scenarios, such as increasing physical activity. For example, while an edge device can measure steps, may the IoT device be deployed to measure the number of steps taken within the user's home. The IoT device can contribute with user-specific data but is often bound to a geographical location. Nevertheless, is the IoT device then able to contribute to context-awareness of the generated data as the device's data type and location are known. For instance, may the edge device know that this data is collected at home due to the signature or metadata of the IoT device. The NuEdge system design allows the data collection to be more comprehensive, vast and adapted to a specific user by integrating IoT devices.

While IoT and smart devices can provide information about the user and environments, it is this under the assumption that sensors and devices can deliver on their services. For example, might an IoT device have limited battery power or not be able to withstand cold temperatures. The limitations of the device might provide insecurity to the collection of data. The NuEdge system has the infrastructure to collect a vast amount of data, however, it is limited by the available resources and reliability of the edge device.

Data management of heterogeneous sources - All integrations and management of data from different sources are pre-programmed to fit the nudge goal of the user. No particular design choice has been proposed to handle heterogeneous data more optimally.

However, as the NuEdge system can be divided into multiple components, edge device, cloud, IoT, and local server, may part of the system logic be performed more locally on each device. For example, could the cloud handle API calls for weather reports, or the local server calculate milestones based on step counter data. The components could perform computational work without depending too much on other components until data needs to be retrieved by the edge device. This way, some of the system logic is decentralized and abstracted, and even more importantly, so is the integration and communication between each component. However, this would demand a standard scheme or communication protocol for sending and receiving data to and from the edge device, as the primary constructor and deliverer of nudges. Integrating heterogeneous sources is not solved in the NuEdge system design.

Efficient processing - The NuEdge system tries to limit data transfer by utilizing edge device resources that are closer to the edge of the network. Lower latency is one promise made by edge computing that contributes to more efficient processing. A personal edge device provides proximity to the user over long periods, provides the smart nudging system with both the availability to nudge the user at any given time, and performs complex analysis based on the vast amount of data collected in local storage. In addition, processing data closer to the edge of the network will provide less data transfer and even eliminate data transfer in certain cases. However, this thesis can not provide sufficient evidence from a quantitative measuring of efficient processing on an edge device.

Privacy and Security - NuEdge system architecture contributes to privacy by isolating sensitive data on the edge device. However, hacking has evolved, and the security mechanisms taken in the NuEdge system cannot guarantee the security and privacy of data. On the other hand, edge computing encourages privacy and protection of sensitive data. Firstly, by isolating data processing of sensitive data within one single device. In addition, is sensitive data only transferred over a local network to be stored on the local server. A local network requires login credentials to join, restricting user access.

Security measurements, like encryption, are available to implement within the NuEdge system but is not investigated as part of the design. The system supports implementing security mechanisms and encourages privacy-preserving storage locations, but has no actual implementations to ensure secure data storage and data transfer.

8.2.2 Security in the Cloud

Looking at the extensive security services offered by the cloud might eliminate the need for a local server in the NuEdge system.

Most cloud service providers offer a large set of features or mechanisms to ensure the security of the cloud. The availability of security features to help the user seems far more extensive than what an individual programmer and local server can offer. Service providers also seem superior in providing security. For example, many service providers distribute and backup data at multiple locations worldwide instead of a local server being the single point of failure. The complexity of the NuEdge system will increase if data has to be backed up on multiple local servers. The edge device is responsible for connecting to all local servers, as the servers themselves cannot communicate over a local network if in different locations. The range of the local server on a local network limits the communication between servers and edge devices.

Additionally, service providers have multiple mechanisms to support the physical protection of data. For example, data is generally kept within locked facilities with surveillance and security guards, as physical protection. The availability and extent of resources of a prominent cloud provider are hard to compete with for smaller businesses wanting scalability at a minimal cost. As the cloud seems to offer more features for both physical and virtual protection of data, may trusting a service provider seems like a better option than a local server for sensitive data storage.

The NuEdge system design relies on the local server for sensitive data storage as off-loading for the edge device. The local server contributes to privacy by limited exposure during data transfer over a local network and limiting user access. However, the cloud may offer more security features with lower cost than a local server.

The main argument made for not utilizing a cloud for sensitive storage is the issue of trusting a service provider. This point is still valid, but one could argue that the benefits gained from trusting the cloud may outweigh the potential damage. Privacy is in many cases, non-negotiable but rather an essential part of any system handling sensitive data. However, it is in the service provider's best interest to ensure the privacy and security of customers' data to secure an income. Prominent cloud providers are dependent on gaining the trust of their customers to store and process their data. Hence, many systems will prioritize low initial costs for scalability and the availability of cloud services rather than relying on a local server as the benefits outweigh the trust issues.

Additionally, the local server may not be able to accommodate a large-scale

NuEdge system with multiple devices. For example, are local servers often stationed and require a local network to gain the security benefits described previously. The edge device is expected to be within reach of a local server to connect and transfer data over a safe connection. However, this may limit the system's adaptability as users change their environment for more extended periods. For example, a user traveling the world for one year cannot connect and off-load sensitive data to a local server stationed at home. Suppose the local server was instead to use WAN. Then, the arguments for security and latency would vanish compared to a cloud, as it can provide the same benefits with the addition of scalability and security services.

The system with a local server would rely on an investment in hardware, proximity to the server, and resources for security mechanisms as software and hardware vulnerabilities are discovered. Since the NuEdge system already utilizes a cloud, the transition for sensitive storage could easily occur in the cloud.

Considering the variety of services offered, scalability, cost, and mobility provided by the cloud, may eliminate the need for a local server in the NuEdge system in the future.

8.3 Evaluation of Edge Computing in A Smart Nudging System

Edge computing has shown the potential to significantly contribute to more efficient data collection in a smart nudging system. Insight into the contributions made by edge computing was gained from implementing a smart nudging system utilizing edge resources. Discoveries include the vast data collection of personal and context-aware data conveniently generated or collected with a mobile edge device.

For efficient processing has edge computing shown to provide storing opportunities and lower latency by limiting data transfer. However, to what extent and if able to replace other storage components in a smart nudging system should be further researched. The effectiveness of edge computing processing is dependent on the resources capabilities such as storage and computational power of the edge device.

Lastly, further research introduces some interesting topics to continue the investigation of edge computing in smart nudging. For example, the introduction of 5G technology may offer edge computing additional support in assisting in a smart nudging system with greater reach and bandwidth. At the same time, larger-scale implementations could test different edge devices' storage and processing capabilities. For further investigation of edge computing, could future innovations and technology advances support and benefit edge computing's role in smart nudging.

8.3.1 Personal and Context-aware data collection

Personal and context-aware data is an essential part of constructing smart nudges. Data is not just part of the nudge as information is shown to the user, but analysis of user-specific data helps determine when, what and how to nudge the user. For example, data delivered in a nudge may be information about aerobics classes at the gym this Wednesday. Data analysis suggests Wednesday due to the user's schedule and aerobics due to user-preferred activities and goals. Edge computing may assist a smart nudging system in collecting personal and context-aware data.

Smartphones as a edge device allows the smart nudging system to benefit from vast data collection. For instance, users interact with their smartphones for many hours per day. The edge device can collect lots of data from the interaction between user and device, such as what are the likes of the user on social media or how often the user checks the news. Such data is valuable for a smart nudging system providing insight into activities based on likes, or when to nudge based on moments of free time identified due to mindless scrolling on the internet.

Furthermore, under the assumption that the user carries the device with them everywhere, would data without the user's interaction also provide insight into user habits and schedules. Sensors on the edge device can collect data in the background, like location or steps. For example, the user may bring their edge device to the gym, going to work, and home, with the edge device registering all locations.

Edge computing can monitor and collect extensive amounts of personal and context-aware data utilizing only edge resources. The potential amount of collectible data on an edge device is huge, as it is able to collect very specific data as edge devices are close to the user and therefore provide the personal data related to the user. With sensors in edge devices are edge computing not dependent on data gained from interaction with the user directly, which is normal for many systems. Edge computing has the opportunity to detect and monitor the user extensively with a personal edge device, or a combination of multiple sensors reporting to the main edge device. The amount and variety of data collection made possible by utilizing edge resources make edge computing a great resource for personal data and context-aware collection in a smart nudging system.

8.3.2 Efficient Processing

Efficient processing in a smart nudging is important to provide accurate analysis and to deliver nudges at appropriate times to the user. For example, yesterday's lovely weather reports are no good for suggesting walking today when it is raining. Edge computing contributes to efficient processing due to user proximity, limiting data transfer as analysis and storage can happen on the edge device alone. However, sharing data from an edge device may make some system resources redundant or unnecessary. Storing data exclusively on the edge device seems inefficient when data is of interest to multiple users. Due to limited scaling of the implementation and time contractions, there are no quantitative research to suggest the actual improvements to be made with edge computing.

Data transfer from data collection decreases with the edge device being close to the user or data source. For example, data being generated on the edge device itself eliminates the need to transfer data from an external source. As a result, edge computing provides lower latency in a smart nudging system during data collection.

Furthermore, since data is collected and stored on the edge device, analysis can take place more efficiently on the edge device. Data does not need to be transferred to a data center for analysis, but rather be performed locally. If not, pre-processing of data to determine relevance may in a smart nudging system speed up processing and minimize unnecessary data transfer. Processing on the edge device can filter out data, limiting the storage on the edge device or other resources storing data. For example, the edge device receives yesterday's weather report and deletes the data as it is irrelevant for today's nudge. The edge device may allow storing and processing data on the edge device, optimizing processing due to proximity to data.

However, storing all data on a single device may seem redundant if multiple users benefit from the same data. For example, two users fetch the same data and calculate the minutes to hike a route. Both edge devices perform the same computational work without sharing the data. One of the main limitations for an edge device is resources and, therefore, should data be shared between users to limit redundant computational work and storage. Sharing of data between multiple edge devices increases communication needs, thus increasing latency.

Data collection, pre-processing, and analysis on the edge device contribute to more efficient processing by limiting data transfer and filtering out irrelevant data. However, quantitative research should be conducted to determine what the actual resource limitations of an edge device are.

8.4 Future Work

This thesis has investigated and found that edge computing may contribute to efficient data collection, and processing in a smart nudging system. However, some challenges has been identified such as sharing complexity and resource limitations. To further investigate how such challenges might be solved or provide more insight into the role of edge computing in smart nudging are some areas suggested for future work.

8.4.1 Remarks and Future Work for the Implementation

After discussing the insight gained from the implementation, it is crucial to realize its limitations or drawbacks. The main ones are the system's overall size and the handling of data from heterogeneous sources. The prototype's limitations help identify areas of improvement for future work on the prototype.

It is common for a system to be deployed large-scale to assess its performance and reliability. However, the implementation can only show a small-scale system of a NuEdge system. The implementation is based on the scenario of one connected user, while in reality, multiple users would be about to join and use the system. The introduction of multiple clouds, edge devices, and sensors is considered ideal for a larger-scale system. The prototype does not support multiple users and lacks data structures to support such a larger-scale system. However, the general architecture and thesis supports the expansion of a NuEdge system with the existing architecture as a basis.

Furthermore, the prototype does not support the joining and leaving of heterogeneous sources. The NuEdge system only provides communication with predefined resources which is integrated beforehand. Integration and communication between heterogeneous sources would provide additional complexity, which is already addressed in section 5.3.

Future work should include the upscaling of the system and provide integration for new heterogeneous sources. The implementation should be able to assist multiple users at different locations running the application on their own edge device. In addition, the system should be able to handle incoming data from any sources to contribute to data collection and personalization. Future work will ensure a more comprehensive analysis of the user and its environment, as well as utilizing the global knowledge from multiple users.

8.4.2 Device capabilities

The main limitation and insecurity of using an edge device in a smart nudging system are limited resource capabilities. Power consumption, storage, and computational resources are all relatively limited compared to large devices or systems.

Furthermore, as the edge device is the user's personal device, may user experience cause restricted resource allocation to avoid lag. For example, data transfer from an IoT device might be paused to let the user play a video instead. In fear of annoying the user by stalling the user activity, should resource allocation algorithms or techniques be investigated.

The thesis could not quantitatively measure or run experiments on edge devices to identify the actual limitations of a specific edge device. Furthermore, the prototype consists only of a single user and therefore cannot conclude if a smart nudging system on an edge device is sustainable for multiple users. Future work should focus on finding out if an edge device is a viable option to host a smart nudging system and the extent of the quantitative limitations of a device.

8.4.3 5G

The edge device is a galaxy 5G, which and having support for 5G, could increase the radius and throughput even further for IoT devices or when connecting to the Azure cloud. Unfortunately, this was not investigated as the 5G network has limited infrastructure and is currently expanding. However, 5G is interesting for the future of smart nudging systems utilizing edge resources.

The emergence of 5G networks provides higher bandwidth and lower latency to accommodate the high demands of new IoT applications. The promises made by 5G include increased data rates, better coverage, and high throughput, contributing to technologies like self-driven cars, drone delivery, and high-resolution video streaming [53]. 5G continues to more efficiently address the ongoing challenges of cellular network,s such as large bandwidth, connectivity, cost, device computational capabilities, and quality of service. Compared to 4G, 5G has decreased latency by 50 percent[53]. However, 5G is a new technology, and there is still a gap between actual implementations and the promises made by the cellular network. Challenges for the 5G network consist of security, as data is exposed during network transfer, and high connectivity, draining device resources such as battery with a large amount of connected devices[53].

8.5 Summary

This section presents an overview of the evaluation chapter and summaries the main takeaways relevant to the research question. The chapter is divided into three parts, each focusing on a different level of abstraction to evaluate the role of edge computing in smart nudging. Firstly, observations from the implementation are presented. These observations give insight into the practical issues of implementing an edge-based smart nudging system. Next, a section evaluates the NuEdge system design. The requirements for a successful smart nudging system are reviewed concerning the NuEdge system design. Lastly is a section evaluating edge computing and its contribution to a smart nudging system in general without a specific design in mind.

The first section presents some observations and lessons learned from implementing a smart nudging system utilizing edge resources. Firstly, is data flow and processing explained. The prototype successfully collects data from different sources, processes it locally on the edge device and then constructs and delivers a nudge to the user. Further, there is a discussion on which communication protocol to use as Wi-Fi presents difficulties with multiple connections on the edge device. The evaluation found that BLE and Wi-Fi, some of the most common communication protocols, had different usage scenarios within the implementation. Wi-Fi is responsible for communication between edge and cloud due to bandwidth and existing infrastructure, while BLE supports simultaneous connections between data resources and the edge device. Furthermore, the implementation reveals a variety of services offered by the cloud to accommodate challenges and optimize the implementation. However, navigating all the different services may provide a challenge in finding the best-suited service for the system.

The second section included the evaluation of the NuEdge system design. The architecture was evaluated according to the requirements for a smart nudging system as described in chapter 6. The evaluation focused mainly on the efficient data collection and processing promised by edge computing, as heterogeneity and security were outside the scope of this thesis. However, both requirements for data management of heterogeneous resources, and privacy and security were evaluated, suggesting that the NuEdge system design does not explicitly offer any advantages but leaves room for further exploration within these areas. The efficiency of the NuEdge system was also problematic to evaluate thoroughly. There was no quantitative research conducted in this thesis to conclude on the actual limitations of edge device capabilities, such as power consumption, storage and computational work. However, lower latency and local data processing contributes to some efficient processing in the NuEdge system. As for personal and context-aware data collection, integrating an IoT device with an edge device was a great source for data collection. The edge device and IoT device can produce personal and context-aware data, which the edge device can collect and process to deliver a nudge. Furthermore, the evaluation concluded that there was a limited need for a local server within the design, due to the number of security services provided by the cloud. A local server can easily be replaced by the cloud in the system and was suggested for future work on the NuEdge system design.

Finally, all the insight from the implementation and the research is combined to evaluate the role of edge computing in a smart nudging system. Compared to the other section, this focuses on the general contribution made by edge computing in a system. The section concludes that edge computing can significantly contribute to a smart nudging system concerning data collection. The mobility and convenience of a personal edge device ensure the collection of personal data for long periods. Moreover, edge computing offers vast data collection conveniently retrieved by the edge device with its sensors or collected from IoT devices. Efficient processing is evaluated to contribute to lower latency. However, there is insufficient research to conclude that processing on the edge device is sustainable enough for large-scale nudging systems. The thesis concludes the scaling of the prototype and quantitative research on resource capabilities such as storage and computational work should be further investigated to determine the sustainability of a NuEdge system. In addition, should the improvements promised by 5G and similar innovations concerning edge computing technologies be researched as future work.

The overall evaluation is, that edge computing can contribute to data collection and some benefits in processing in a smart nudging system. However, limitations and future research around the capabilities of edge devices should be investigated to determine the sustainability of an edge-based smart nudging system.

9

Conclusion

The research question of this thesis was to investigate what role edge computing may have in a smart nudging system. From theoretical research and the practical implementation of a smart nudging system utilizing edge resources, the contributions made by edge computing was sought to be revealed. Especially in regards to data collection and processing was the goal to determine the use of edge computing in a smart nudging system, discovering both advantages and limitations. Furthermore, the implementation provided a proof of concept with edge computing in a smart nudging system in a real-world scenario.

Research on smart nudging identified four main requirements for a successful smart nudging system. These requirements was used to evaluate the impact edge computing could make in smart nudging system. Furthermore, a discussion on the possibilities and limitations of edge computing provided insight into how a smart nudging system could utilize edge computing resources most efficiently. As a result, a smart nudging system, NuEdge, was proposed integrating an edge device, cloud, local server and IoT. The main contribution of the edge device and IoT were to optimize the data collection and processing of the system. Additionally, the cloud and local server would assist the shortcomings of the edge device regarding resources capabilities such as storage and computational power.

A prototype based on the NuEdge system design was implemented as a proof of concept. The implementation of the system provided insight into the possibilities of edge computing in smart nudging and its usefulness in a real-world scenario to improve physical health. The implementation helped discover limitations and benefits to different communication protocol used in the prototype. BLE was found to be more suited for IoT devices, while Wi-Fi is most common for integrating the cloud over the internet. It also revealed the extensive services provided by the cloud, which suggested to remove the local server from the NuEdge design.

From the investigation of edge computing and smart nudging combined with observations from the prototype, edge computing has proven to impact the efficiency of a smart nudging system. The primary contribution identified is the convenience of personal data collection and the vast amount which is collectible with an edge device. In addition, lower latency and analysis performed on the edge device may affect and improve edge processing. However, further research should test edge device capabilities, and explore how the introduction of 5G can affect the use of edge computing in smart nudging.

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