ADAPT: Approach to Develop context-Aware solutions for Personalised asthma managemenT

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Mario Jose Quinde Li Say Tan
M00620761

Faculty of Science and Technology
Middlesex University London

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Acknowledgements

To my parents, Dilcia Ysabel and Juan Ignacio. Thank you for all the sacrifices both of you made so that I have the opportunities you did not have when you were children. Some people say that luck does not exist, but being born as your son is my special definition of being lucky.

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Abstract

The creation of sensors allowing the collection of a high amount of data has been possible thanks to the evolution of information and communication technology. These data must be properly interpreted to deliver meaningful information and services. Context-aware reasoning plays an important role in this task, and it is considered as a hot topic to study in the development of solutions that can be categorised under the scope of Intelligent Environments.

This research work studies the use of context-aware reasoning as a tool to provide support in the asthma management process. The contribution of this study is presented as the Approach to Develop context-Aware solutions for Personalised asthma managemenT (ADAPT), which can be used as a guideline to create solutions supporting asthma management in a personalised way.

ADAPT proposes context-aware reasoning as an appropriate tool to achieve the personalisation that is required to address the heterogeneity of asthma. This heterogeneity makes people with asthma have different triggers provoking their exacerbations and to experience different symptoms when their exacerbations occur, which is considered as the most challenging characteristic of the condition when it comes to implementing asthma treatments. ADAPT context dimensions are the main contribution of the research work as they directly address the heterogeneity of asthma management by allowing the development of preventive and reactive features that can be customised depending on the characteristics of a person with asthma. The approach also provides support to people not knowing their triggers properly through case-based reasoning, and includes virtual assistant as a complementing technology supporting asthma management. The comprehensive nature of ADAPT motivates the study of the interaction between context-aware reasoning and case-based reasoning in Intelligent Environments, which is also reported as a key contribution of the research work. The inclusion of people with asthma, carers and experts in respiratory conditions in the experiments of the research project was possible to achieve thanks to the collaboration formed with Asthma UK.

List of Acronyms

AA Asthma Attack

ACAC Asthma Control Assessment Component

ACQ Asthma Control Questionnaire

ADAPT Approach to Develop context-Aware solutions for Personalised asthma managemenT

API Application Programming Interface

ATS American Thoracic Society

BTS British Thoracic Society

C-AR Context-aware Reasoning or Context-awareness

CBR Case-based Reasoning

CO Communication feature

COMEAP Committee on the Medical Effects of Air Pollutants

CTM Control Test Management

EHRs Electronic Health Records

FEV_1 Forced Expiratory Volume in 1 second

FEV_6 Forced Expiratory Volume in 6 seconds

FVC Forced Vital Capacity

GINA Global Initiative for Asthma

GPRS General Packet Radio Service

Health-ITUEM Health IT Usability Evaluation Model

ImHS Interactive mobile Health System

IoT Internet of Things

MR Medication Reminder feature

NE Notification Engine

PEF Peak Expiratory Flow

PM Personalised Monitoring feature

PM10 Particulate Matter 10

PM2.5 Particulate Matter 2.5

PO-CBR Process-Oriented Case-based Reasoning

POSEIDON PersOnalised Smart Environment to increase Inclusion of people with DOwn's syNdrome

RA Respiratory Arrest

S2T Speech to Text

U-CIEDP User-Centric Intelligent Environment Development Process

T2S Text to Speech

TA Triggers Assistance feature

VA Virtual Assistant

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Chapter 1

Introduction

This chapter provides the background that is needed to understand the research problem addressed by the research work reported in this thesis. The main concepts related to asthma and its condition management are explained in section 1.1. Context-aware reasoning, case-based reasoning, and their application fields are described in sections 1.2 and 1.3. The problem statement and the objectives of the research work are presented in section 1.4. Finally, the structure of the thesis is outlined in section 1.5.

1.1 Asthma

This section presents concepts related to asthma in order to facilitate the understanding of the technologies that are later associated with the management of the condition. The definition of asthma and its classification are described. Further, the main approaches to treat the condition, and the main challenges of its management are then explained.

In the International Consensus Report on Diagnosis and Treatment of Asthma, asthma is defined as a chronic inflammatory disorder of the airways that causes some symptoms in susceptible individuals [77]. These symptoms are usually linked to the widespread and variable airflow obstruction, which is often reversible. The inflammation also increases airways responsiveness to a variety of stimuli. The Global Initiative for Asthma (GINA) defines asthma as a heterogeneous disease, associating its definition to a history of variable expiratory flow limitation together with respiratory symptoms such as wheeze, shortness of breath, chest tightness and cough that vary over time and intensity [108].

In 2015 in the US, 24.6 million people were diagnosed with asthma, 11.5

million people had one or more asthma attacks, and 3 thousand people died from asthma [28]. In 2015 in the UK, 5.4 million people were diagnosed with asthma, every 10 seconds someone suffered a potentially life-threatening asthma attack, 3 people died from asthma every day, and the annual cost to the NHS of treating asthma was more than £1 billion [11].

The origin of asthma is not completely understood, and there is no cure for it yet [49, 117]. However, it can be controlled with a daily plan to avoid triggers and reduce symptoms [10, 12, 109]. Understanding the heterogeneity of the condition is the key to acknowledge the importance of the daily plans. The heterogeneity of asthma can be explained by stating that each person with asthma may have different triggers provoking their asthma attacks, and may experience different symptoms when their attacks occur. The heterogeneity of their triggers means that diferent triggers would provoke asthma attacks, however, not all people with asthma are sensitive to the same triggers. The heterogeneity of their symptoms goes beyond as they may even vary from day to day or night to day for the same person with asthma [117].

1.1.1 Asthma classification

The heterogeneity of asthma makes it difficult to provide a unique classification of the condition. Aetiologically, it can be classified into intrinsic and extrinsic. Symptoms of people suffering from *intrinsic asthma* cannot be associated with an environmental allergen, and symptoms of people suffering from *extrinsic asthma* are linked to an environmental allergen [77]. Triggers in intrinsic asthma are non-specific irritants (e.g. stress, exercise), while triggers in extrinsic asthma are specific allergens (e.g. pollen, mould) [117]. Figure 1.1 shows examples of triggers for intrinsic and extrinsic asthma conditions.

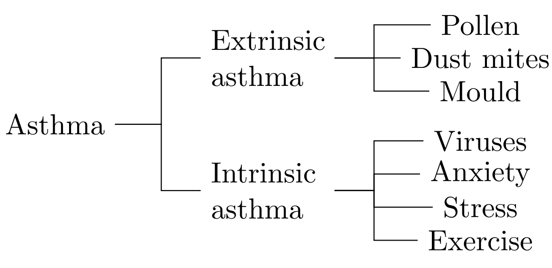

Figure 1.1: Aetiological classification of asthma: examples of triggers

The aetiological classification helps to define preventive plans, but it does not differentiate levels of severity. A classification based on severity is important as it aids to define the actions required to reduce symptoms. It also allows differentiating levels of exacerbations, which helps to define the actions to take in case of emergency. Asthma can be classified according to its severity by considering the lung function and the clinical features existing before treatment [77]. Lung function is defined by measuring the person with asthma's maximum speed of expiration (Peak Expiratory Flow or PEF). This value represents how constricted their airways are. Figure 1.2 shows the types of asthma according to its severity.

People suffering from *mild asthma* experience intermittent brief symptoms less than twice a week and nocturnal asthma less than twice a month. They are asymptomatic between exacerbations, their PEF is greater than 80% of their predicted one, their PEF variability is less than 20%, and their PEF goes normal after using a bronchodilator.

People suffering from *moderate asthma* experience exacerbations more than twice a week or nocturnal asthma symptoms more than twice a month. They require to inhale beta$_2$-antagonist almost daily. Their PEF is between 60% and 80% of their predicted one, and the variability of their PEF is between 20% and 30%. Their PEF goes normal after using bronchodilator.

People suffering from *severe asthma* experience exacerbations or nocturnal asthma frequently. Their symptoms are continuous, and their physical activities are limited by their condition. They have been hospitalised because of asthma in the previous year, or they have suffered a life-threatening exacerbation before. Their PEF is less than 60% of their predicted one, and the variability of their PEF is greater than 30%. Their PEF is still below normal despite applying optimal treatment.

The characteristics of the types of asthma that are shown in Fig. 1.2 may overlap for some people given the high heterogeneity of the condition. However, people with asthma usually belong to the most severe type in which any feature occurs [77]. For example, a person may have all the characteristics of a person with mild asthma, though if they have been hospitalised for asthma in the previous year, then their asthma should be categorised as severe.

Asthma exacerbations are always life-threatening and can occur at any asthma severity level. Thus, knowing the severity of an asthma exacerbation is relevant. Having a classificationn of exacerbations considering the PEF and symptoms of the people experiencing exacerbations is useful in the urgent or emergency care setting. Figure 1.3 summarises the classification provided in Ref. [122], in which asthma exacerbations are categorised as:

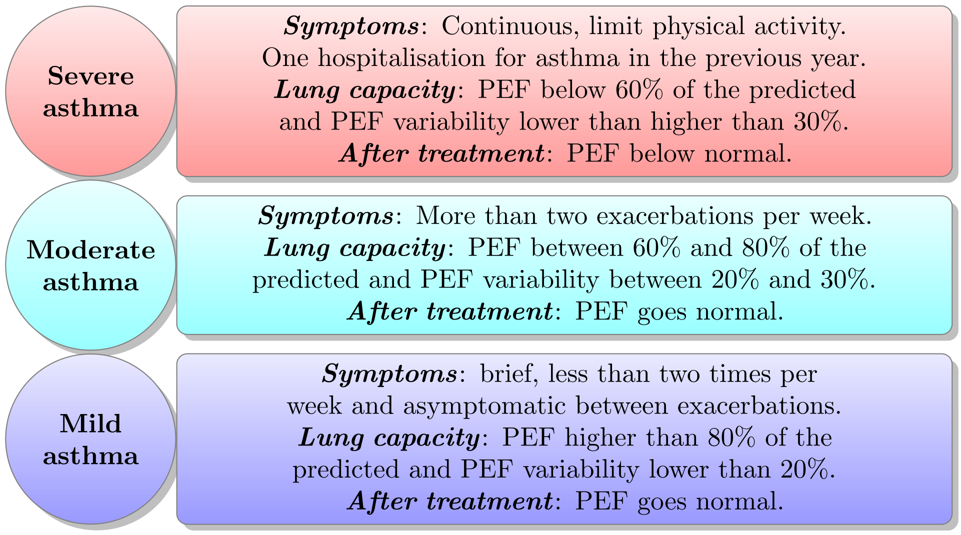

Figure 1.2: Classification of asthma based on severity

- *Mild exacerbations*: Dyspnea appears only with physical activity. PEF is higher or equal to 70% of the predicted one or their personal best;
- *Moderate exacerbations*: The person shows dyspnea interfering with or limiting usual activity. The PEF of the person with asthma is between 40% and 69% of their predicted one or their personal best;
- *Severe exacerbations*: The person shows dyspnea at rest interfering with conversation. Their PEF is lower than 40% of their predicted one or their best;
- *Life-threatening exacerbations*: The person is perspiring and too dyspneic to speak. Their PEF is lower than 25% of their predicted one or their personal best.

1.1.2 Challenges in asthma treatment

Self-management is a set of tasks people must carry out to live with chronic conditions. When it comes to asthma, it highlights the issues of dealing with a variable condition, and the ability to recognise and act according to the symptoms and signs of asthma deterioration [107].

The goal of asthma management is to achieve control of the condition. The British Thoracic Society (BTS) assigns the *complete asthma control* level to a patient not having daytime symptoms, not waking during the night due to asthma, not needing rescue medication, not experiencing asthma attacks,

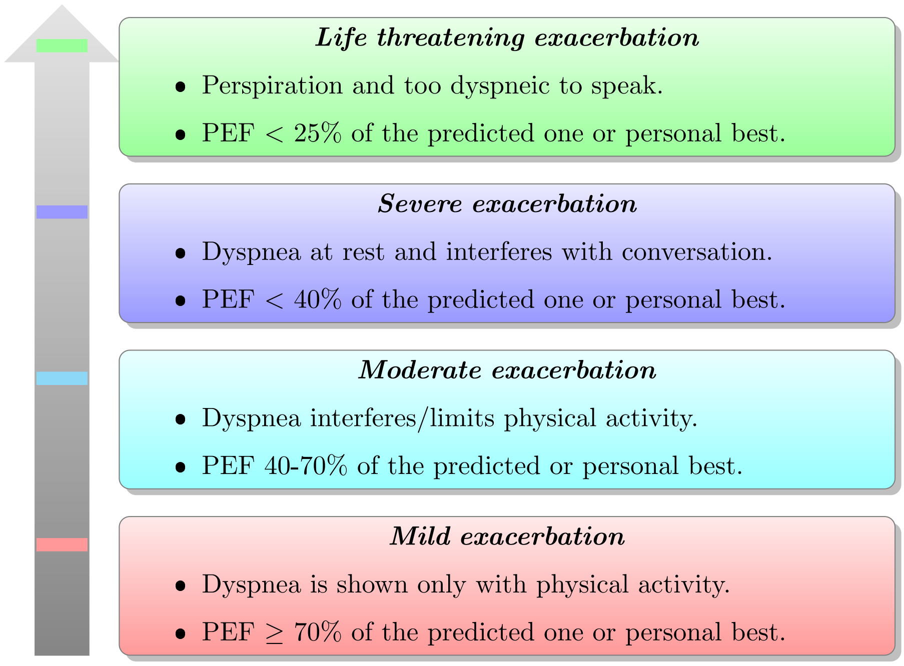

Figure 1.3: Classification of asthma exacerbations

not limiting their regular activities, having normal lung function and suffering minimal side effects from medication [107]. GINA assesses the control level of a patient by defining how well controlled their symptoms are and how likely they are to suffer a future exacerbation [108].

BTS and GINA highlight the importance of patients education in the success of asthma management programmes. They also suggest to include pharmacological and non-pharmacological strategies in these programmes. Pharmacological strategies aim to achieve asthma control through medication, and non-pharmacological strategies are based on avoiding triggers to improve control and reduce medication usage [107, 108].

GINA suggests using the *control-based asthma management cycle* that facilitates a stepwise approach to finding the optimal pharmacological strategy for people with asthma. The treatment can be chosen and adjusted from five choices or steps, each one stronger than the previous [108]. Although the BTS does not explicitly suggest the use of a cycle, it recommends using six pharmacological levels in which people with asthma can move up or down until finding their optimal treatment [107].

Table 1.1 shows a comparison between the pharmacological treatments suggested by the BTS and GINA. Explaining the classification of asthma medication is important to understand this table. *Controller medications* are

Table 1.1: GINA and BTS guidelines for pharmacological treatments

GINA		BTS	
Step 1	–	Level 1	Monitored low-dose of controller
Step 2	Low-dose of controller	Level 2	Low-dose of controller
Step 3	Low-dose of 2 controllers	Level 3	Low-dose of 2 controllers
Step 4	2 or more controllers in higher doses	Level 4	Regulate the dose of the 2 controllers
Step 5	Add-on treatment	Level 5	Add another drug
–	–	Level 6	Add oral steroids or alternative treatments

Note: All steps and levels include the use of reliever medication as needed.

regularly used to decrease inflammation, symptoms and future risks. *Reliever/rescue medications* are used in case of worsening asthma or exacerbations. *Add-on therapies* must be used in patients whose symptoms are persistent in spite of having used optimised treatments [108].

Asthma management plans are difficult to implement because people with asthma are heterogeneous. The triggers of their symptoms are different, and the development of their condition depends on many factors. Hence, healthcare givers cannot provide a *one-fits-all* guideline for people with asthma and, conversely, asthma treatments must be personalised for each of them [126]. Pijnenburg & Szefler [85] clarify the importance of personalisation in asthma management by explaining that sometimes stepping down treatments for patients is as important as stepping up.

One of the main challenges of implementing management plans for asthma is collecting information from heterogeneous people to define and adjust their customised treatments. This makes it important to consider the specific characteristics of their asthma in the definition and implementation of their asthma management plans. However, Osuntogun & Arriaga [81] show that physicians can know how is the condition of the people with asthma they treat only when they go to the medical centres for regular visits (approx. twice a year) or for emergencies. Hence, it can be argued that collecting the data related to someone's asthma would allow healthcare givers to deliver better-personalised treatments in less time by analysing more information about the current health status of a person with asthma.

The inclusion of people interested in the condition of a person with asthma (stakeholders) is another important challenge to address. Yun et al. [126] show

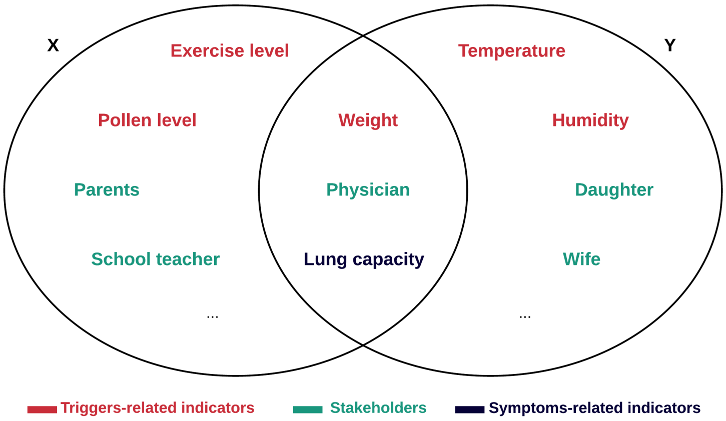

Figure 1.4: Context example of two people with asthma

the example of a mother that left her job because it was tough to manage her daughter's moderate asthma. In the same study, another mother reported that managing her daughter's mild asthma was interfering with her job. This is evidence supporting the fact that implementing asthma management treatments is difficult as it involves changing daily activities of families, even when the asthma is not severe. Thus, defining the information that the main stakeholders require, the format in which they require it and the right moment when they require it can be extremely useful and should be considered in the development of solutions supporting asthma management.

This section discusses the fact that the heterogeneity of asthma is one of its most challenging characteristics. This heterogeneity makes people with asthma sensitive to different triggers inducing their exacerbations, and to experience different symptoms when their exacerbations occur. Because of this, the concept of personalisation is important in asthma management and, from this point of view, defining what is relevant to monitor is one of the keys to implement an asthma management plan. This means that each person with asthma assigns different levels of relevance to the information units building the background to manage their asthma. This set of information units and their relevancies frames the context of a person with asthma. Thus, solutions implementing context-aware features can support the asthma management process as they can react to what is important for each person with asthma.

Figure 1.4 illustrates a comparison example between the contexts of two people with asthma. The set shown on the left (set X) is part of the context of a male asthmatic child whose triggers are demanding exercise and pollen. Thus, his context includes exercise level and pollen level in his nearby to help him preventing exacerbations. Parents and school teachers are part of his context as they are interested in knowing his status (stakeholders) in order to take actions in case of a deterioration of his health. His physician is also a stakeholder as they are interested in knowing how his condition evolves. Lung capacity is an indicator of his health status and weight is a long-term indicator helping to improve the control level of his condition.

The set shown on the right (set Y) of Fig. 1.4 represents the context of a male adult with asthma that is vulnerable to high levels of humidity and sudden temperature changes. In this case, knowing the temperature and humidity levels of the places he frequents is important to prevent exacerbations. These indicators are part of his context. The patient has a wife and a daughter old enough to assist him in case of emergency. Hence, they are also part of his context as stakeholders. Lung capacity, weight and their physicians are common elements of the contexts of the two people represented in Fig. 1.4.

Figure 1.4 helps to clarify how the contexts of two people with asthma differ depending on the characteristics of their conditions and their personal situations. The context of a person with asthma is made of the elements that are relevant to manage their condition. Thus, although the contexts of two people may include some common elements, they are likely to be different.

People with asthma usually go through a *trial-and-error* process until they get to know their condition properly. The example shown above is based on the assumption that the contexts of the two people with asthma are well known and can be represented. This means that they know what their triggers and symptoms are and, thus, they are able to define and implement the management plans they need in order to achieve the control of their condition. Nevertheless, getting to this point of knowledge about their condition is mostly difficult to achieve.

There is a list of 27 potential triggers and 14 potential symptoms that can be made by collecting the information provided by organisations doing research on asthma [10, 12, 107, 108]. This means that people with asthma have to narrow down this list until finding out what their triggers and symptoms are. For this, they usually have to remember what happened when they experienced a deterioration in their health status. This *trial-and-error* process is risky as the person does not know what preventive measures to take.

The process of discovering the triggers of a person with asthma will be referred in this thesis as the *uncertainty stage* of asthma management. The uncertainty stage is not only related to recently-diagnosed people with asthma that are discovering what affect them. People that move to a place where they are exposed to triggers they were not exposed before have to go through the uncertainty stage again. Further, people whose asthma is evolving (i.e. their triggers and symptoms are changing) go through the uncertainty stage again.

The uncertainty stage is considered as another important challenge in personalised asthma management mainly because of the risks associated with it. The main concern at this stage is the fact that, as it was explained previously in this section, any asthma exacerbation can be life-threatening at any asthma severity level. Personalisation plays also a key role in addressing the uncertainty stage not only because the triggers and symptoms to discover are specific to the person with asthma, but also because their daily activities are those defining the exposure they need to be aware of to discover their triggers.

1.2 Context-aware reasoning

Surveys related to context-awareness [7, 84] state that the most acknowledged definition for *context* and *context-awareness* is given in Ref. [3, 35], in which context is defined as *"any information that can be used to characterise the situation of an entity, where an entity can be a person, place, or physical or computational object"*. Context-awareness -which is also known as *context-aware computing or context-aware reasoning*- is then defined as *"the use of context to provide task-relevant information and/or services to a user"*.

A person going to a specific supermarket can be used as an example to explain these concepts. The entity, in this case, is the person, and the situation is reaching the supermarket. Some information characterising this situation is the location of the person and the location of the supermarket (context). Then, a context-aware solution would be a mobile application showing to the person the shortest path to get to the supermarket. This example gets more complex if more elements are added to the situation. For instance, if the person is disabled, the context-aware solution should consider the available disabled services before recommending the path to follow.

The definitions of context and context-awareness given in Ref. [3, 35] go from the system to the user. The person-centric approach used in this research project goes from the user to the system, which makes the user the element that defines what the relevant contexts are. From this point of view, context can be defined as *"the information that is directly relevant to characterise a situation of interest to the stakeholders of a system"*. Context-awareness is then defined as *"the ability of a system to use contextual information in order to tailor its services so that they are more useful to the stakeholders because they directly relate to their preferences and needs"*.[1]

Context-awareness is considered a core feature of Pervasive/Ubiquitous computing [16, 84]. Acampora et al. [4] also acknowledge context-awareness as one of the main characteristics of Ambient Intelligence allowing the use of contextual and situational information to personalise services. Furthermore, given the fact that Intelligent Environments are built on the concepts of Pervasive/Ubiquitous Computing, Smart Environments and Ambient Intelligence [16], context-awareness can also be associated with Intelligent Environments.

The application of context-awareness will be analysed from the Intelligent Environments perspective. Eight emerging applications in which context-awareness plays a key role will be explained. These applications are related to Transportation, Education, Production places, Smart offices, Intelligent supermarkets, Energy conservation, Entertainment and Health [16].

The application of context-aware systems to *Transportation* is already delivering benefits. GPS-based spatial location is one of the best tangible examples of using context to improve the transportation system. With the appropriate algorithm, it is possible to analyse drivers' context (location, speed, route, etc.) for making transport more fluent, efficient and safe. Waze [120] and Google Maps [42] are two examples of applications gathering and analysing drivers' context with the aim of providing them with services to avoid traffic or hazards. Google Maps also supports users to find the best route using public transport and bicycles, and even walking.

The application of context-awareness in *Education* aims at supporting staff and students to obtain better results. It can be used to create smart classrooms using innovative learning methodologies that improve the learning process and support students and lecturers' activities outside the classroom. An example of this is given in Ref. [34], in which a virtual assistant able to dynamically interact with users and to provide answers to context-specific questions was designed and evaluated showing positive results.

Workplaces can benefit from context-aware solutions. Companies can improve their *Production-Oriented Places* by using sensors (e.g. RFID) to tag and track products. An example of the benefits in this application is aiding

[1] The definitions of context and context-awareness were provided by J.C Augusto.

the supply chain management by providing relevant information to deal with changes in the demand of the products offered by companies [104, 119]. The implementation of *Smart Offices* is another application example of context-awareness in the workplace. Offices with the right equipment can aid employees to increase their efficiency when performing their tasks by taking into account their context [16].

Intelligent supermarkets use context-awareness to enhance the shopping experience of customers. These supermarkets are made of objects that interact with customers by interchanging visual and auditory information. This allows the collection of data that will be used to determine the contexts of the customers. These contexts are then used to provide them with more suitable products and services. An example of a model supporting the creation of *Intelligent supermarkets* is the "Ubiquitous User Model Service" that provides contextual information about customers' profiles, actions, characteristics and location in the supermarket [116].

Smart homes are the main example of using intelligent environments to control lighting and temperature in an automated way. It helps to improve *Energy conservation* by optimising the consumption of energy resources. A simple example of this is controlling the heating system of a house through a mobile application allowing users to set the desired indoor temperature and the time in which people will be at home with the aim of avoiding having the heating on when no one is in there. Another example is setting the lights to turn on only when someone is inside a room. Context-awareness also has the capacity of enhancing users' *Entertainment* experience by using devices that provide a more immersive gaming experience [16].

Health-related applications of context-awareness are able to increase the efficiency of health services and safety. Given the fact that this research project is focused on health, application examples of health context-aware systems are shown in chapter 2.

1.3 Case-based reasoning

Case-based reasoning is a type of artificial intelligence that simulates *"the use of old experiences to understand and solve new problems"* [61]. A more practical explanation of case-based reasoning is provided in Ref. [2], in which it is explained as a problem-solving paradigm that reuses information and knowledge from previous situations that are similar to a new problem to solve.

Aamodt & Plaza [2] explain case-based reasoning describing the case-based reasoning cycle, which is made of four processes that are also known as *"the four REs"*: retrieve, reuse, revise, and retain. The *retrieve* process of the case-based reasoning cycle refers to finding the most similar case or cases to the one that is being assessed. *Reuse* is about using the solution of the most similar case that was found in the *retrieve* process, as the most suitable solution for the case that is being solved. The *revise* stage consists in confirming whether the reused solution is correct or not. Finally, *retain* refers to store the new case with its confirmed solution in the database of cases with the aim of using it to assess future problems.

The case-based reasoning cycle shows how the technique solves a new problem based on the knowledge that has been gained from similar problems that were previously solved. The database of cases represents the knowledge that is made of previous experiences that are stored in the form of cases. The *retrieve* and *reuse* stages reflect the process of using the previously gained knowledge to solve a new problem. The *revise* process verifies whether the solution that was proposed to solve the new problem is valid or not. Once this verification is done, the new problem that was solved is store in the *retain* stage in order to increase the database of previously solved cases.

Case-based reasoning as a research topic is gaining momentum [36, 51], and has been studied in several domains like legal reasoning, web services, and health sciences [74]. Successful application examples of case-based reasoning in the healthcare and industrial domains are shown in Ref. [74, 75], which highlight the flexibility of case-based reasoning as one of the benefits of the technique for being applied in fields where experiential knowledge is easy to be collected and reused.

The application of case-based reasoning methods for process and workflow management is known as Process-Oriented Case-based Reasoning (PO-CBR). This application field aims to create and adapt workflows based on cases capturing the knowledge from previous activities related to modelling, executing and monitoring workflows [71]. An example of a PO-CBR system is the one proposed by Dufour-Lussier et al. [38]. The core of the system is a method that automatically acquires cases from procedural texts (especially from instruction text) and generates workflows based on these cases. The system was used to generate workflows from cooking recipes, and its evaluation showed a 75% recall and 94% precision performance.

Case-based reasoning has also been used to improve performance in production places. Wan et al. [118] propose a system implementing case-based reasoning techniques for maintenance planning. The system is a knowledge-based machine tool maintenance planning system whose application layer includes a knowledge reuse component that is achieved through case-based reasoning techniques. The other layers of the system aim at facilitating information and knowledge sharing among the stakeholders of the process. The system improves efficiency of maintenance planning, and it is an example of case-based reasoning complementing other techniques in a multi-modal system.

Research on using case-based reasoning in construction has also been done. An overview of the application of case-based reasoning in construction management shows that this application domain is increasing, especially since 2006, and identifies 17 construction management application fields in which case-based reasoning techniques have been used. One application example is given by Zima [127], who uses case-based reasoning to support the process of cost estimation at the preliminary stage of a construction project. Another example is given by Soto & Adey [103], who use case-based reasoning to estimate resources for construction projects.

Given the subject of this research work, the application of case-based reasoning in healthcare is explained in chapter 2, section 2.2 with the aim of providing a deeper analysis of this application area.

1.4 Problem statement

Section 1.1 shows that personalisation is the key issue to address when it comes to design and implement asthma management treatments. This is because of the high heterogeneity level of the condition, which makes people have different priorities considering the specific characteristics of their asthma. This personalisation is required in the implementation of the pharmacological and non-pharmacological strategies that are part of asthma management plans. Thus, personalisation has to be considered over all the stages and dimensions of asthma condition management.

Despite the importance that personalisation has in asthma treatments, no research has been done in proposing solutions allowing users to customise the indicators to monitor nor the features to use, depending on the characteristics of their asthma management plans. As it is more thoroughly explained as part of the state-of-the-art in chapter 2, only the research work presented in Ref. [126] vaguely acknowledges the importance of personalisation by suggesting to customise technology probes to support the families of people with asthma. The importance of this customisation is explained from an IT literacy perspective, in which it is stated that families should consider their IT literacy in the decision of choosing the right technology to support the asthma management process in which they are involved. This research work was published almost 10 years ago and no research related to personalisation of asthma management plans has been done since then.

The stage in which people with asthma do not know their triggers properly is challenging because they should go through a trial-and-error process that exposes them to having asthma attacks more frequently. Recently-diagnosed people with asthma are those that usually go through this stage, which will be referred in this research work as the *uncertainty stage*. People moving to a new place (e.g. a new city) in which they are exposed to substances they were not exposed before may also go through the uncertainty stage. Furthermore, it is known that someone's asthma may evolve over time, which means that their triggers and symptoms may change, so when this happens they have to go through the uncertainty stage again.

Context-awareness and case-based reasoning can aid in addressing the personalisation issues of asthma management. Context-awareness is potentially capable of addressing the personalisation that is associated with customising the services a solution supporting asthma management should offer when a person knows their triggers and symptoms. For this, it is important to being able to define the context of a person with asthma proprely. However, context-awareness cannot deal with the uncertainty stage by itself, so case-based reasoning can complement it in order to build synergies that can cope with the needs of people with asthma at this stage. Hence, it will be possible to use contextual information and adapt it to procedures and reasoning strategies [73] that, in this case, are related to asthma management plans.

There are no research works formalising the application of context-awareness together with case-based reasoning in intelligent environments. As it is explained in more detail in section 2.3, few research works have focused on formalising the integration of both concepts even outside the scope of intelligent environments. Most of them describe the way they should work together to achieve a specific context-aware feature. However, they do not explore deeply in how case-based reasoning should interact with other context-aware features not implementing case-base reasoning in their logic. This is important to explore because intelligent environments are expected to be enriched with several context-aware services that are accomplished through different techniques. Furthermore, the use of case-based reasoning for intelligent environments has not been tested in a real life setting including the collection of contextual data from people during their regular activities as input of the case-based reasoning cycle.

This research project studies the use of context-awareness together with case-based reasoning for the development of solutions aiding personalised asth–ma management. The main contribution of the research project is the use of context-awareness to allow the customisation of the features of these solutions, considering the characteristics of the person with asthma that is being supported. Their context is used to deliver preventive and reactive features to support personalised asthma management, and it includes health-related and non-health-related elements. The definition of the context of a person with asthma is considered as the most important part of the contribution because it is the basis to develop other features aiding decision-making in asthma management. Case-based reasoning is studied as a mean to provide support to context-aware solutions in the uncertainty stage of asthma management. The interaction between both concepts that is proposed in this research work is meant to support people with asthma and their stakeholders in a comprehensive way that considers the delivery of several similarly important features aiding preventive and reactive tasks in asthma management.

1.4.1 Aims and objectives

The aims of the research project and the objectives are listed below. The aims and objectives enumeration do not indicate that they have been achieved sequentially. Unlike this, they were achieved following a methodology that allows to accomplish them gradually. This methodology is explained in chapter 3.

A1 To identify the main benefits and challenges of using context-awareness for personalised asthma management.

A1-O1 To identify the benefits and gaps of existing context-aware solutions supporting asthma management.

A1-O2 To match the benefits of context-awareness with the main concerns of people with asthma and carers about asthma management.

A2 To design and validate an approach that can be used to develop context-aware solutions supporting personalised asthma management.

- **A2-O1** To create an approach to develop context-aware solutions for personalised asthma management.
- **A2-O2** To validate the approach proposed in **A2-O1**.

A3 To formalise the interaction of context-awareness and case-based reasoning to support personalised asthma management.

- **A3-O1** To propose and evaluate the use case-based reasoning to support personalised asthma management in the uncertainty stage.
- **A3-O2** To define the interaction between context-awareness and case-based reasoning to support personalised asthma management.

1.5 Thesis structure

This section outlines the structure of the next chapters of the thesis.

Chapter 2 discusses the state-of-the-art of the research areas that are related to the research project reported in this thesis. This part of the study puts a special focus on the application of context-awareness and case-based reasoning for asthma management, and the interaction between context-awareness and case-based reasoning in intelligent environments.

Chapter 3 provides details about the methodology that led the research project. The methodology is explained under the framework of the User-Centred Intelligent Environment Development Process. The initial stage experiments of the project are also presented in this chapter. The initial stage experiments are those that, along with the literature review, aided to define the scope of the research project reported in this thesis.

Chapter 4 presents the main contribution of the research, which is the Approach to Develop context-Aware solutions for Personalised asthma managemenT (ADAPT). The elements of the approach and the interaction among them are explained. From these elements, ADAPT context dimensions are the most important contribution of the research project because they allow to describe the context of a person with asthma properly, which can be used to develop personalised features that can address their needs better. This chapter also reports on three experiments. Two of these experiments evaluate the application of case-based reasoning for personalised asthma management. The other one illustrates the use of virtual assistant technology as part of ADAPT.

Chapter 5 presents the experiment that was done to validate ADAPT. Just like for most of the experiments that were part of this research project, real users were involved in the validation of the approach. Finally, the discussion and conclusions of the research project are shown in chapter 6.

Chapter 2

State-of-the-art

This chapter presents the previous work that is considered relevant to the research areas associated with this research project. The state-of-the-art is divided into three sections whose aims are showing the recent research works that have contributed to the study of context-awareness and case-based reasoning in asthma condition management.

Section 2.1 shows the literature review of context-awareness in asthma management. For this, an explanation of the application of context-awareness in healthcare is exposed from an ambient intelligence perspective that classifies its application into six groups [4]. Context-aware systems are described as illustrative examples facilitating the explanation of context-awareness applied to healthcare. Section 2.1.1 then presents the analysis of the existing context-aware systems for asthma management that were found in the literature review. This analysis discusses the main benefits and gaps of the systems.

Section 2.2 and 2.3 provides an overview of the application of case-based reasoning in asthma management. Section 2.2 shows application examples of case-based reasoning in the health sciences before exposing the only research work exploring the application of case-based reasoning in asthma management (section 2.2.1). Finally, section 2.3 presents the analysis of previous research works that have used case-based reasoning together with context-awareness. This is important because it is directly linked to one of the subjects of this research work, which is studying the interaction of context-awareness and case-based reasoning to address the uncertainty stage of asthma management.

2.1 Context-awareness in asthma management

There is a strong link between context-awareness and intelligence evironments. The origin of context-awareness is associated with the need to improve human-computer interaction in research areas like ubiquitous computing. Intelligence evironments are built based on three concepts: pervasive and ubiquitous computing, smart environments, and ambient intelligence. Pervasive/ubiquitous computing is related to providing users with distributed and context-aware computational services that can be used across different environments. Smart environments are environments enriched with sensing devices that facilitate the collection of data to determine context. Finally, ambient intelligence involves software assisting people in their activities. This software translates context into sets of rules to deliver relevant information regarding the situation [16]. From this perspective, context-awareness is used to interpret what users need [56].

The application of context-awareness in healthcare, from an ambient intelligence perspective, can be classified into six groups [4]:

- The *continuous monitoring* group includes systems mostly using non-invasive sensors to monitor patients. These systems can monitor health conditions, which is useful to aid the control of chronic illnesses in which typical measures are taken during occasional visits only. They can also monitor behaviour, which aid assisted living settings like those related to individuals with mental disabilities. Detecting emergency situations, e.g. fall detection, is another application of this type of systems.

- The *assisted living* group is made of ambient intelligence solutions using automation to support people with disabilities in achieving more autonomy in their daily activities. These systems provide continuous cognitive and physical monitoring and assist people in real-time. Some application examples of these solutions are assisting the elderly, improving medication management and supporting people suffering from dementia and visual impairment.

- The *therapy and rehabilitation* group systems can fulfil the rehabilitation needs based on sensor networks and ambient intelligence. Autonomous rehabilitation and therapy can be achieved by equipping patients with wireless and wearable sensors that allow the collection of real time data about their rehabilitation and therapy processes.

- The *persuasive well-being* group is made of systems that aim at motivating people to change towards healthier lifestyles. An example of this group is using games as a way of helping obese children to improve their eating habits and reduce weight.

- The *emotional well-being* group is made of systems detecting emotions through sensors that recognise physiological changes (like blood pressure, bpm, respiration), and analyse audio and gestures. These systems can also aid emotions management.

- *Smart hospitals* are built using ambient intelligence to facilitate the communication among nurses, doctors and other stakeholders in a hospital. Contextual information (e.g. location, profile, availability) is used to provide support in hospitals daily activities. Holzinger et al. [46] highlight the importance of context-awareness in the creation of *Smart hospitals* by acknowledging the adequate use of context as a future challenge in the subject.

Medication Assistant is an example of using context-awareness to improve people's health. It is a mobile application whose aim is to address the problem of medication non-adherence in older adults. Medication Assistant focuses on age-related factors (such as inherent medication increase, cognitive losses and demotivation) not allowing the elderly to follow proper medication management. Multimodality and context-awareness are used to provide advice and support in the medication management of older adults [106].

The Hefestos wheelchair is another example of a system using context-awareness to support people in their daily activities. It is an intelligent system considering users' profile and their contexts to provide resources for wheelchair accessibility through a mobile device. In this case, context is mainly linked to the physical places the users frequent (e.g. building, room, street) and the features of these places that are associated with accessibility (e.g. ramps, lifts, assistance). The results of the qualitative research performed to evaluate Hefestos showed 98% of acceptance in perceived usefulness [105].

Context-awareness can also be used to help people in emergency situations. SOSPhone is a mobile application allowing users to make emergency calls through an iconographic interface running in touchscreen mobile devices. The solution assists people having problems in making emergency calls, which can be caused by disabilities (e.g. hearing loss, deafness) or trauma situations (shock/panic situations under emergencies). The application allows users to contact emergency centres by choosing the icons representing the occurrence and answering simple questions. An SMS describing the situation is then created and sent to the emergency centre. The SMS includes the profile and location of the user, and the information selected by them [82].

The development of technologies that can improve quality and efficiency of healthcare processes is always a concern because of the relevance that health has in people's quality of life. When it comes to chronic diseases, this concern is even more relevant because the number of people suffering from it is increasing. Two of the main reasons of this increment include the fact that illnesses that were mortal in the past are now treated as chronic conditions [34], and the strong link between the rise of chronic conditions and the ageing population [47].

Different types of solutions are being used to aid the management of chronic conditions because, despite the resources focused on it, there has not been a relevant success in finding cures for them [44]. The community-centred care, which is one of the trends that are converging to shift the US healthcare paradigm, is one of these solutions. Its aim is focusing on lifestyle management to prevent and cope with chronic conditions [101]. Context-awareness, from this point of view, can help to improving lifestyle management by enhancing the monitoring and control of chronic illnesses [50, 85].

Researchers are aware of the critical role that technology plays in self-management. Osuntogun & Arriaga [81] state that technological solutions supporting continuous care and management of patients with chronic conditions are increasing. Isakovic et al. [50] suggest using mobile applications as tools for self-monitoring. Samples et al. [101] explain the opportunity of using mHealth to improve health outcomes and reduce costs by empowering patients in their self-management processes. Finally, Harvey et al. [34] describe technologies that can be used to control chronic conditions and adjust lifestyle by monitoring patients' status in real time.

The development of technology, especially in the field of mobile devices and wireless connectivity, has allowed the creation of context-aware solutions aiding the management of chronic conditions. An example is a context-aware system that increases accuracy when measuring blood pressure [115]. This system is made of four sensors (2 for the feet, 1 for the seat and 1 for the back) whose aim is to ensure that patients sit and rest for five minutes with their back supported and their feet flat on the ground, before measuring their blood pressure. The evaluation of the system confirmed that it increases awareness and improves patients' technique.

The home-based rehabilitation system for cardiovascular diseases called HeartHealth is another example of using technology to improve lifestyle management. Its aim is improving adherence to prescribed exercises in the rehabilitation process of cardiovascular diseases. The system is loaded with the exercise programme a person must do at home, and simulates a game based on their programme. The system uses a camera and image recognition techniques to assess whether the patient is doing the rehabilitation exercises properly or not. After the analysis of this context, it provides feedback to the patient and their healthcare professionals [31].

The Interactive mobile Health System (ImHS) is an example of using context-aware solutions to support diabetes management. It monitors blood-glucose of diabetes patients to determine their health status and to execute actions depending on that status. The ImHS uses a General Packet Radio Service (GPRS) Blood-Glucose Monitor to collect patients' blood-glucose level. This information is uploaded to a cloud server to determine the patient's health status after analysing it. The system also performs automated actions such as notifying caregivers when the patient's status is critical [30].

2.1.1 Existing context-aware systems for asthma management

There are research works that have reviewed mobile applications supporting asthma self-management. Belisario et al. [70] studied if smartphone and tablet applications for asthma self-management are effective tools for supporting patients with asthma to self-manage their own condition. After the experiments, the authors stated that, although asthma self-management applications were potentially beneficial in the asthma management process, the use of this technology to support asthma self-management was still in its early days and it was not possible to reach firm conclusions about the potential effect of asthma applications. However, Wu et al. [123] typified the commercial mobile health applications for asthma that were available on iTunes store and Google Play. One of the findings of this work shows that mHealth applications have a great potential to improve care of asthma but it is not possible to demonstrate quality, effectiveness and protection of users' data in most of them.

Huckvale et al. [48] analyse the evolution of mobile applications for asthma, concluding that the market landscape is made of low-quality generic information applications. The information offered by these applications is a concern because of the potential risks of clinically-relevant impact resulting from in-adequate content. The applications do not support individuals in changing behaviour nor offer tools allowing the communication between professionals and patients. They are not likely to satisfy evidence-based recommendations for information content, nor the design of self-management tools. The research also shows that most of the applications offer simple peak flow diaries or very basic background information about the condition. Moreover, the applications do not focus on the gaps in asthma management.

Research on developing and validating technology to support asthma management at different stages have been done. Lefco et al. [68] study the use of icons in the design of asthma mobile health tools supporting parents of young children. The outcomes of the research suggest that using icons may improve parents reaction to their child's asthma symptoms. Chamberlain et al. [29] propose and test a mobile platform able to diagnosed people suffering from asthma and chronic obstructive pulmonary disorder, showing promising results. MyAirCoach is another example of technology supporting people with asthma. It is a mobile application whose aim is to improve the education component of asthma management plans [57]. Finally, the use of mobile applications supporting the asthma self-management responsibility transition from parents to adolescents has also been studied in Ref. [39, 100].

Table 2.1 presents three devices that can be used to track asthma symptoms. The first analyses cough sound, the second focuses on diaphragm motion and the third measures lung capacity. An explanation of these solutions is given below.

Al-khassaweneh et al. [6] propose a solution to record and analyse cough sound with the aim of recognising the health status of a person with asthma. Using cough sound in asthma is important because it is the only symptom in some cases. The system uses a keypad to start and stop the process, a microphone to record cough sound, and an LCD to display the diagnosis of the cough sound after analysing it with an algorithm developed using MATLAB. The results of the test showed that the solution correctly classified about 85-90% of the recordings. The researchers suggested that the proposed system can support parents to monitor their children asthma process.

Liu & Huang [69] use an ultrasound probe to monitor the diaphragm motion in the respiratory process of a person with asthma, with the aim of discovering patterns. After analysing diaphragm motion, four templates were identified. One template for normal breathing, and the other three for frequent coughing, breathing faster and shortness of breath, respectively. Although no device was developed, it is stated that these templates can be used to design a portable ultrasound device to detect and predict asthma attacks.

Natarajan et al. [76] present a cost-effective device called Audioflow, which is a PEF meter able to communicate with smartphones through the headphone (audio) jack. The device measures the maximum flow rate exhaled, and can be used to monitor their lungs capacity by measuring their airways obstructions. The device was validated, and met the spirometry standard given by the American Thoracic Society (ATS) Standard regarding PEF meters.

There are research works proposing more comprehensive solutions supporting asthma management. Tables 2.2, 2.3 and 2.4 summarise the details of the research works delivering applicable solutions to monitor more indicators that support decision-making for asthma management in a more comprehensive way. More details of these research works are given below.

Osuntogun & Arriaga [81] propose a system that keeps record of the symptoms and medication usage of a person with asthma. For this, the system sends a questionnaire as an SMS asking for these details. The person then replies to the SMS providing information about their symptoms and medication usage. The system collects, processes and makes these data available to be reviewed by the patient and healthcare professionals. The research work addresses the fact that physicians are only able to know relevant data about their asthma patients in the consultations, hospitalisations and emergency visits. The use of a dashboard showing relevant information about patients to physicians (physician dashboard) is proposed. Moreover, it is suggested to send alarms to physicians about specific concerns, and merge the system with the Electronic Medical Record.

Yun et al. [126] studied how technology probes can be used to manage paediatric asthma patients. A qualitative research including three families was performed after asking them to use a system made of three components. The first one is a temporal data management application called Salud! that allows users (patients and relatives) to enter and visualise data. The second one is an indoor quality sensor that monitors indoor air quality. The third is a multifunction widget installed in a computer where users can check the outdoor air quality index based on the the ZIP code of their home, and register the values from the PEF meter and indoor quality sensor into Salud!

The results of the experiment done by Yun et al. [126] were overall positive. It was found that the collected data helped to recognise patients' symptoms and triggers easily, which was also motivating and engaging for the patients and their families. It was also shown that the level of technological support should be personalised to each family, depending on the severity of the patient's condition and the users' technological practices. The main drawback of the system is that users must enter data about patients in a non-automated way. This means that, after using the PEF meter and checking the indoor quality index, users needed to enter these values into Salud! by using the multifunction widget. This is important to consider because people tend to stop using systems altering or slowing down their activities. Other drawbacks include the system not allowing communication with healthcare professionals and not detecting potential risky situations.

Al-Dowaihi et al. [5] propose mBreath, which is an asthma monitoring system on the go. mBreath allows to use a PEF meter device that automatically sends measures to the smartphone via Bluetooth. Users can also answer simple questions through their smartphones in order to define their control level. The system uploads these data, allowing medical staff to check it through a web-based interface. Another feature is notifying patients and their doctors when their PEF readings are less than their normal condition. It also provides users with weather announcements, notifications about sand storms and an educational module.

The validation of mBreath showed that it was recognised as satisfactory, useful and effective for asthma management. The researchers proposed to add more features like integration with pollution sensors and monitoring patients' location to suggest the location of nearby hospitals in case of emergency [5]. Nevertheless, if mBreath is compared with the other solutions, it can be argued that the analysis of the context of the person with asthma is only based on the PEF reading to identify emergencies. It does not consider other important factors that can enhance decision-making in preventive situations (e.g. air pollution). Moreover, the weather information provided by the system is not specific enough to warn patients about their closest environment as the weather announcements are related to the city where they live in.

Table 2.1: Examples of devices used to monitor asthma symptoms

Research	Tracked symptom	Devices	Details	Benefits (+) and drawbacks (-)
[6]	Cough sound	Keypad	Analyse cough sound to detect the different status of a person with asthma. An alarm is shown when an asthma attack is present.	+ Coughing is the only symptom for some types of asthma. – Portability: low – Automation: low – Accuracy: 85-90
[69]	Diaphragm motion	Ultrasound probe	Analyse diaphragm motion in the respiratory process of asthma patients.	+ Templates to identify irregular symptoms were developed. + Allows real time analysis. + Automation would be high. – Portable ultrasound device does not exist yet.
[76]	Lung capacity	Audioflow: PEF meter	Audioflow connects to smartphones through the headphone (audio) jack. An application processes the audio frequency to know the PEF measure.	+ Meets the ATS Standard + Automation: medium -– high + Portability: high – Does not allow real time analysis.

Table 2.2: Patients' indicators monitored by the reviewed solutions

Research	PEF	FEV_1	FEV_6	FVC	NO	CO	O_2	Blood O_2	HR	RR	Wheezing	Motion	Exercise	Medication	Control level
[81]	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	✓
[126]	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–
[5]	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	✓
[113]	–	–	–	–	–	–	–	–	–	–	✓	✓	–	–	–
[63]	✓	✓	✓	–	✓	✓	✓	–	–	–	–	–	–	–	–
[9]	–	–	–	–	✓	–	–	–	–	–	–	–	–	–	✓
[99]	✓	✓	–	✓	–	–	–	✓	–	–	✓	–	✓	✓	–
[37]	✓	✓	–	✓	–	–	–	–	✓	✓	✓	✓	–	–	–

Table 2.3: Environmental indicators monitored by the reviewed solutions

Research	Overall air quality	Temperature	Humidity	CO	O_3	NO_2	Cl	VOC	Weather announcements
[81]	–	–	–	–	–	–	–	–	–
[126]	✓	–	–	–	–	–	–	–	–
[5]	–	–	–	–	–	–	–	–	✓
[113]	–	–	–	–	–	–	–	–	–
[63]	–	–	–	–	–	–	–	–	–
[9]	–	✓	✓	✓	–	–	–	–	–
[99]	–	✓	✓	✓	✓	✓	✓	–	–
[37]	–	✓	✓	–	✓	–	–	✓	–

Table 2.4: Other features of the reviewed solutions

Research	Automation	Notifications	Stakeholders	Virtual Assistance
[81]	Low	None	Healthcare professionals	No
[126]	Low	None	Family*	No
[5]	Medium	Alerts of weather changes and when PEF is below normal.	Healthcare professionals	No
[113]	Unknown	None	None	No
[63]	Medium	None	Healthcare professionals	No
[9]	Medium–High	Reminders to take readings once a day.	None	No
[99]	Medium–High	Alert patients when context is not normal.	Healthcare professionals	No
[37]	High	None	None	No

*Family were subjects in the qualitative research done to validate the proposal, not information recipients.

Uwaoma & Mansingh [113] propose a monitoring system only using smartphones built-in sensors. It monitors patients' activity by strategically placing the smartphone on their body, and wheeze sound through the smartphone microphone. An algorithm recognising deviations from the patient's activity baseline was also developed to aid activity monitoring. The algorithm classifies the recorded wheeze sounds into three types: normal respiratory sound, baseline sound and wheeze sound. The research work suggests to include medical knowledge in the algorithm, use machine learning techniques to increase robustness, and use the built-in capabilities of smartphones to monitor temperature (thermometer), humidity (hygrometer) and air pressure (barometer).

Using only built-in smartphone capabilities is the main feature of the proposal reported in Ref. [113]. Thus, although the HCI of the system is not specified in the research work, it is expected that a highly automated solution can be developed from this research work because it uses only built-in smartphones capabilities. However, developing a solution that fully depends on built-in smartphones capabilities would be difficult to spread and standardise because mobile devices from different brands and models have different quality standards in the production of their components. For example, if the microphone and audio processing capabilities of the smartphone are not good enough, then the process to classify a wheezing sound will be unreliable.

Kwan et al. [63] created a system able to connect with mobile devices that work on Android OS. It is made of two components: a portable external mobile device and a software application. The mobile device monitors health status by measuring PEF, Forced Expiratory Volume in 1 second (FEV_1), Forced Expiratory Volume in 6 seconds (FEV_6), and the following chemical breath biomarkers: Nitric Oxide (NO), Carbon Monoxide (CO) and Oxygen (O_2). The application collects and stores these measures, and sends them to a physician through e-mail. The main benefit of this system is its ability to collect different indicators framing patients' context. This diversification is important as it reduces uncertainty in the analysis of the context of a person with asthma. The main drawback is that the system does not include the collection of environmental data to support the decision-making process. Adding this feature is critical because people with asthma are heterogeneous, and it would provide more information about the triggers and symptoms, and enhance preventive measures.

Anantharam et al. [9] adapted kHealth (a platform that enhances decision making and improves health, fitness and well-being) to support asthma management. The system uses two sensors: a sensor that determines the inflammation level in the lungs by monitoring the respiration NO level, and a sensor drone monitoring temperature, humidity and CO levels from the environment. Another component of the system is a mobile application that sends reminders to take NO level readings once a day, collects data from sensors, and gathers the answers of a questionnaire to establish patient's control level.

It is important to highlight that Anantharam et al. [9] suggest the following to improve the system: adding more sensors to track more indicators, using *"all-in-one"* and passive sensors to improve usability, allowing the patient's doctor to give instructions through the mobile application, and sending alerts to patients and their guardians when an emergency is detected. Moreover, by comparing the system to others, it can be said that its main advantage is its capability of providing a solution with a high level of automation, and the inclusion of environmental indicators.

Ra et al. [99] developed AsthmaGuide as an ecosystem to monitor someone's asthma and provide advice. The system collects physiological and environmental data, and sends it to a smartphone hub that uploads the data to the cloud. Wheezing sounds, information about lung capacity and blood oxygen level are collected through an electronic stethoscope, a spirometer and a pulse oximeter, respectively. Temperature, humidity, CO, Ozone (O_3), Nitrogen Dioxide (NO_2) and Chlorine (Cl) levels are gathered through a sensor drone. Environmental data are obtained by using the zip code provided by the patient. Finally, information about medication dosage and exercise is manually entered by answering 10 multiple choice questions.

AsthmaGuide is the most comprehensive of the systems that have been reviewed. One of its most important features is its capacity to classify lung sounds to detect wheezing. The system also notifies healthcare providers and patients when the collected data indicates deterioration in the patients' health status. Furthermore, it includes a cloud web application that can be accessed by patients and healthcare providers to review patients' data. Other relevant features include alerting patients when the air quality is unhealthy, and assisting patients depending on their health status with very general expert advice from existing asthma standards. Doctors that were included in the qualitative research performed to validate Asthma Guide stated that the system could also be used to support other lung problems.

Dieffenderfer et al. [37] built a low-power wearable sensor system made of a wristband, a chest patch and a portable spirometer. The wristband collects the patient's motion and nearby exposure (O_3, volatile organic compounds, temperature, relative humidity). The chest patch gathers heart rate, respiratory rate, acoustic signals (wheezing) and skin impedance. The handheld spirometer is used to obtain the FEV_1, PEF and Forced Vital Capacity (FVC) to define lung capacity and airways obstruction level. The devices use the Bluetooth Low Energy standard to connect with an integration device (laptop, tablet or smartphone) that uploads the data to the cloud.

The system proposed in Ref. [37] is the most automated one that was reviewed, in spite of the handheld spirometer. It allows to monitor people with asthma continuously. It is designed to use components consuming less energy, and was successfully tested in a controlled environment. Furthermore, the authors suggest (i) to use the proposed sensor system with the aim of gathering information to develop an algorithm that predicts asthma attacks, (ii) to allow physicians to review the collected data in order to study how activity level, ozone and VOC exposure affects people with asthma, and (iii) to keep doing research for reducing the power consumption level of the system.

2.1.2 Critical analysis

This section analyses the existing context-aware solutions supporting asthma management that were explained in section 2.1.1. The solutions are analysed from four points of view.

Variety of indicators

Tables 2.1, 2.2 and 2.3 show the indicators tracked by the reviewed solutions. The wide variety of indicators tracked by these systems is evidence to reconfirm the heterogeneity of asthma that is explained in section 1.1. Furthermore, Huckvale et al. [48] show that most of the mobile apps for asthma only offer to record peak flow diaries and to provide information content -whose level of quality is a concern- about the condition. This is also evidence confirming that monitoring indicators framing the context of people with asthma is a difficult task. The findings in Ref. [48] also show that this is an emerging area which is worthwhile to explore.

The patients' indicators monitored by the solutions are shown in tables 2.1 and 2.2. It can be seen that these indicators are very different from one solution to another. Thus, different people with asthma would choose different solutions according to the characteristics of their condition as a consequence of the heterogeneity of their asthma. For instance, someone whose asthma is triggered by exercise will choose to use the solutions proposed in Ref. [37, 99, 113] because they are able to monitor motion and/or exercise. On the other hand, someone whose treatment is only using a reliever inhaler when necessary would not mind choosing a solution not tracking their medication-related context.

The environmental indicators monitored by the reviewed solutions are shown in table 2.3. The research works are ordered from the oldest to the most recent one, which means that only the three most recent solutions [9, 37, 99] can track environmental indicators. From the others solutions, one considers the overall air quality from a zip code zone but without separating it into more detailed substances [126], while another implemented a weather announcements component warning users about sandstorms [5]. The fact that only the most recent solutions are able to monitor environmental indicators would be a consequence of sensors -and the APIs allowing to access the data collected by these sensors- being more available and affordable in recent years.

People with asthma can benefit from context-aware solutions because it helps to address the high heterogeneity level of the condition. This characteristic makes people with asthma have different contexts. For example, areas with high levels of pollution could be considered part of the context of a patient whose asthma is triggered by high levels of CO_2, while temperature could be considered part of the context of a patient sensitive to sudden temperature changes. Hence, solutions implementing context-awareness are able to provide patients with services that can be personalised according to the specific characteristics of their condition. Alerting a person with asthma about possible hazards considering their triggers and notifying them to take their medication considering the specific treatment they must follow are examples of personalised context-aware features.

This large diversity of indicators that need to be monitored brings relevant challenges for context-aware systems supporting asthma management. First, the heterogeneity of the condition makes patients need different sets of sensors to track their specific contexts. This counters the suggestion of building *"all-in-one"* sensors to improve the usability of mHealth systems [9] as it is not cost-effective to build a customised device combining the specific sensors that are needed to gather the specific context-related data of a person with asthma. Second, the necessity of using different sensors to model their contexts makes the integration of the collected data challenging as sensors could be from diverse providers. These challenges are linked to achieving the integration among the sensors that collect the context-related information of different people with asthma.

Automation level

The automation level is another interesting characteristic to analyse from the reviewed research works. As it can be seen in table 2.4, the automation level of the solutions supporting asthma management has increased over time. This can also be considered as evidence of the technological development that have occurred in recent years allowing the creation and spread of more automated sensors/devices. The systems proposed in Ref. [81, 126] are considered to have a low automation level as they require users to enter their data manually into the system by using SMS [81, 126] or a widget installed in the computer [126].

The systems proposed in Ref. [5, 63] have a medium automation level. Both systems include a mobile application automatically storing the measurements taken by the patient into the systems. Because of this, they are considered to have a higher automation level than the previous research works (Ref. [81, 126]). Nevertheless, their drawbacks from an automation perspective are: (a) mBreath [5] still requires patients to answer five question to define their control level; and (b) the system proposed in Ref. [63] allows patients to send an email with the readings using the native operating system email application instead of automatically notifying stakeholders, and consolidating and uploading the data to a server for showing special reports to stakeholders.

kHealth [9] and AsthmaGuide [99] are considered to have a medium-high automation level. kHealth, after being set up to aid asthma management, is able to gather information about the indoor environment, air quality and exhaled NO through a mobile application automatically. Although kHealth also requires patients to answer questions to define their control level, the number of sensors included in the solution is high, and the fact that it reminds patients to take readings makes it a solution with a higher automation level than the previous ones. AsthmaGuide automatically collects data from several sensors through a smartphone, though it also asks patients to enter their medication dosages and answer questions to define their control level.

The system proposed in Ref. [37] has the highest automation level from all of the reviewed systems. The chest patch and wristband collect patients' data (heart rate, respiration rate, wheezing, motion, temperature, humidity, and level of O_3 and VOC). Lung capacity (PEF, FEV_1 and FVC) is collected through a spirometer. These data is sent to an integrating device via Bluetooth

Low Energy technology. Although the system does not include an automated notification system, its architecture to collect data is the most automated one. This makes it easier to collect data, which is relevant as one of the aims of the system is to use these data to develop an algorithm capable of detecting asthma attack onsets.

The features of smartphones and tablets aid to build more automated solutions. The devices used in Ref. [5, 9, 63, 99] collect data that is later sent to a smartphone or tablet, which is used as integration devices. Isakovic et al. [50] state that smartphones and tablets are the best integration devices because of their processing and storage capabilities, and wireless connectivity features. However, the use of smartphones and tablets as integration devices brings an important challenge: battery duration. These devices usually do not have long working periods because of their battery duration [40]. This does not allow to deliver ubiquitous solutions and delays acceptance of mHealth solutions [114]. The main reason for the high battery consumption is the typical architecture of mHealth applications in which mobile devices and applications exchange data with smartphones/tablets and the cloud through Bluetooth and wireless Internet connections.

Notification component

Table 2.4 shows details about the notification components of the reviewed research works. It is important to point out that only three [5, 9, 99] of the eight systems implement some kind of notification features. Although the system proposed in Ref. [81] does not implement any notification feature, the authors suggest alerting physicians by using alarms. Furthermore, the authors of Ref. [9, 99] consider the notification component as a relevant part of the system, and they also suggest to improve that component as future work.

The notification features are different for each system. mBreath [5] sends alerts to patients when their PEF readings are below normal or when the weather is close to change. Being aware of these changes is relevant in some regions where the weather can be a hazard for people with asthma. The mobile application proposed in Ref. [9] sends reminders to take readings once a day. AsthmaGuide [99] notifies a person with asthma if their context is not normal, and can also trigger alarms or advice messages depending on how abnormal their context is.

People with asthma are the main targets of the notifications components, however, other relevant stakeholders of the asthma management process are not included as recipients of notifications. Although people with asthma are the main stakeholders because their lives are the most affected by the condition, other people (or sometimes institutions) would also be targets of some type of notifications. A simple example is parents being interested in knowing when the PEF readings of their asthmatic child are below normal as an indicator of a decrease in their child's lung capacity. Another example is them being notified when the environment of their house can be a hazard to their child. By having this type of notifications, parents would be more aware of their child health status, take measures to improve their health status, and avoid exposing them to hazardous situations.

Personalisation

Section 1.1 shows that the concept of personalisation is strongly linked to asthma because of the high heterogeneity level of the condition. Personalisation is especially important to define the treatment for each patient. The definition of the non-pharmacological treatment needs to consider their clinical history to know the triggers inducing their exacerbations, and the symptoms evidencing a decrease in their health status. Moreover, the level of medication to use by each patient must also be customised by stepping the patient up or down until finding their optimal pharmacological treatment.

Only one research work [126] highlights the importance of customising technology probes to support families of people with asthma. This work suggests that the severity of the person's asthma and the skills of their family members have to be considered when choosing the technology to support them. Thus, it can be said that the severity of a person with asthma defines the technology required to monitor their context and how frequent their context must be monitored. The technological skills of their families are linked to the mHealth's IT literacy challenge, which can limit the number of potential users [8] as a consequence of people having different ways of adapting to technology [114].

IT literacy shall be considered as a restriction, however, the special characteristics of a person with asthma provide the most relevant constraints to personalise their treatment. None of the reviewed research works provides or suggests to allow users to choose the services nor the indicators to monitor according to the main characteristics of their asthma, nor provide support in the uncertainty stage of asthma management. This drawback is linked to the explanation provided in section 2.1.2, where the high variety of sensors/devices required to track indicators is highlighted. From a personalisation perspec-

Table 2.5: Gaps in using context-awareness to aid asthma management

Gap	Description
Personalisation	None of the solutions allows people with asthma to set up the indicators they need to track according to the characteristics of their condition.
Notifications	The notification components of the reviewed solutions do not consider all the relevant stakeholders in the asthma management process of a patient.
Outdoor environment	The reviewed research works do not use the information collected by networks of weather and air quality stations tracking outdoor environmental data.
Location	Solutions do not take advantage of the location tracking capabilities of the integration devices.
User adoption & acceptance	There is a lack of research works studying the acceptance and adoption of technology supporting asthma management.

tive, this drawback is analysed from a requirements engineering point of view, highlighting the requirement of delivering personalised services.

This section provided a critical analysis of the solutions supporting asthma management that were described in section 2.1.1. The analysis highlights the main benefits and drawbacks of the systems from different perspectives in order to provide insights to develop context-aware solutions aiding asthma management. Table 2.5 summarises the gaps that were found from the analysis of the research works using context-awareness to support asthma management.

2.2 Case-based reasoning in asthma management

Case-based reasoning allows reusing information and knowledge from previous situations that are similar to a new problem to solve [2]. Case-based reasoning problem-solving paradigm has found in the health science a promising application domain [21] because it can handle some issues better than other methods and techniques [26]. It has been used in the health sciences providing support different tasks [18]. One future direction of case-based reasoning in the health sciences is adapting procedures and reasoning strategies to personal constraints described by contextual information itself [73]. Asthma management fits under this category as recently diagnosed people need to discover their triggers and symptoms for adapting their plans to their personal constraints. This personalisation process can benefit from using case-based reasoning.

Case-based reasoning has been applied in the health sciences from its beginnings [21, 22]. One of the main reasons of this is the similarity between the case-based reasoning cycle and the decision-making process that is used in the health sciences [21, 23, 26, 45], where expert knowledge plays a major role and evidence-based practice is generalised [24]. Some examples of this match are the use of case histories in the training of health care professionals, the high amount of anecdotes about the treatments of individual patients in the medical literature, and the adaptation of general guidelines to specific individuals based on recorded practical cases [22].

There is evidence to affirm that health sciences is a growing application research area for case-based reasoning [18, 21, 22, 23, 24, 25, 26]. Case-based reasoning systems in the health sciences can be classified based on their purpose-oriented properties into five categories: diagnosis, classification, tutoring, planning, and knowledge acquisition/management [18, 78]. Moreover, hybridisation of case-based reasoning with other artificial intelligence techniques to create multimodal reasoning systems is possible to achieve, which is promising to handle large, complex and uncertain data in clinical environments [18, 23].

Miotto & Weng [72] propose a framework that can be used as an illustrative example of case-based reasoning in the health sciences. The framework uses case-based reasoning to identify eligible patients for clinical trials from electronic health records (EHRs). The target patient for a specific trial is represented by a set of cases that are made based on the EHRs of already enrolled participants for the trial. Case-based reasoning is then applied to assess whether someone is eligible for the trial or not. The system also provides a rank of potentially eligible patients. The evaluation of the framework shows, among other results, that the use of case-based reasoning improves the efficiency of the process by modelling only on minimal trial participants.

There are several application examples of case-based reasoning in health care. Bach et al. [17] show how it supports the decision-making process of selfBACK, a system aiding the management of non-specific low back pain. Case-based reasoning is used in the development of the selfBACK clinician dashboard whose aim is to facilitate co-decision making among patients and clinicians. Patient-specific recommendations of the self-management component are tailored through the application of case-based reasoning to exercise, education and physical activity contents for low back pain treatment.

Saraiva et al. [102] show another example of case-based reasoning applied to healthcare by proposing a medical diagnosis decision support model for gastrointestinal cancer. The research presents a multimodal (hybrid) system using rule-based reasoning to improve the case-based reasoning retrieval process. The output of the model is the probability of the patient having a specific cancer, and it uses case-based reasoning to simulate the general practitioner behaviour. The results of applying the hybrid approach demonstrate a higher accuracy than using case-based reasoning only. The validation shows that the model would be helpful and that general practitioners are willing use it.

Case-based reasoning has also been applied to support people suffering from chronic diseases. Yuan et al. [125] propose a hybrid system aiming at minimising the number of times that a person with diabetes needs to measure their sugar levels every day. The system implements a case-based reasoning cycle in order to determine and predict the blood sugar level of a person with diabetes. Another illustrative is given by Begum et al. [19], who propose the use of case-based reasoning to provide decision-support in stress management. For this, finger temperature signals of a person are processed using case-based reasoning as the core technique to provide a stress diagnosis.

2.2.1 Existing systems using case-based reasoning for asthma management

Case-based reasoning has been used in the development of the knowledge support system for asthma care services proposed in Ref. [112]. The system is meant to be used by inexperienced physicians in the process of diagnosis and treatment prescription. For this, patient's data is collected through a laboratory test and a questionnaire. Expert opinion can also be used as input data. The system uses case-based reasoning to retrieve the case that is the most similar to the patient, based on the input data. The selected case is then used to define the asthma care plan for the patient. If there are no similar cases, the system stores it as a new case for future use. This system is, to the best of our knowledge, the only research work studying the application of case-based reasoning in asthma condition management.

2.3 Context aware and case-based reasoning

There are examples of context-awareness and case-based reasoning being used together. Kwon & Sadeh [64] propose the use of case-based reasoning to replace the buyers utility function, which is complex to determine, in a multi-agent intelligent system aiding context-aware comparative shopping. Kumar et al. [62] also apply both concepts to e-commerce by building a recommendation engine based on two CBRs that stores users and products contexts, respectively. Zimmermann [128] uses case-based reasoning to provide recommendations to users in a museum guide context-aware system. MyMessage is a context-aware system using case-based reasoning as an alternative to analytic hierarchy process in order to achieve message filtering [65]. Lee & Lee [67] use context-awareness and case-based reasoning to improve the performance of a music recommendation system.

A recent survey on using context-awareness together with case-based reasoning shows that, despite the potential synergies of using these concepts together in the development of intelligent environments, there is a lack of research on the subject [56]. Leake et al. [66] describe the research opportunities of using case-based reasoning in smart homes, mostly focusing on delivering personalised services. An example of using both concepts together to develop ambient intelligence is given by Kofod-Petersen & Aamodt [59, 60], who developed a system using case-based reasoning to achieve contextualised ambient intelligence. The system was validated in a hospital ward by configuring it to detect situations occurring there. Ospan et al. [80] provide another example in this application domain by using context-awareness and case-based reasoning to develop a virtual assistant capable of solving conflicts based on users' preferences in a smart home.

There is a lack of formal methodologies aiding the application of context-awareness together with case-based reasoning in the development of intelligent environments. Khan et al.[56] explain the advantages and challenges of using both concepts together to build intelligent environments. They show that the benefits of merging both methods outweight its challenges, but it also highlights that no formal way of merging them has been proposed. Pla et al. [86] show that, even outside the scope of intelligent environments, there are no many approaches aiming at improving the perfomance of CBR with contextual information. In order to address this gap, they propose three methodologies that are assessed using a breast-cancer diagnose database enriched with geospatial context. Yuan & Herbert [124] propose a hybrid framework for pervasive healthcare that uses fuzzy logic in the retrieval and adaptation processes of the CBR cycle. The framework was validated through a simulation in a smarthome laboratory but not using data from real users.

The analysis of the research works reviewed show that case-based reasoning and context-awareness are usually merged together in two ways. The first one is using case-based reasoning as the main tecnique that deliver the required context-aware feature [59, 60, 62, 67, 124, 128]. The second one is using case-based reasoning to replace a subprocess that is too complex to be executed in a more traditional way but that is needed to complete the main process that will deliver the context-aware feature [64, 65]. Nevertheless, to the best of our knowledge, there is no research done on using case-based reasoning not only to achieve a desired context-aware service but to interact with other context-aware features that are similarly complex and important in the creation of more comprehensive systems. From an intelligent environments point of view, it is important to formalise this interaction because intelligent environments are expected to be enriched with several context-aware services that are achieved by implementing different techniques in their logic.

2.4 Chapter summary

This chapter presented the state-of-the-art of context-awareness and case-based reasoning for asthma condition management. The main benefits, opportunities and issues in the subject that have been shown are useful to understand the importance of the proposal. One of the outcomes of this section shows a lack of research on creating solutions supporting personalised asthma management. Another outcome is the lack of support that solutions provide to people with asthma going through the uncertainty stage. Case-based reasoning was presented as a suitable technique to provide support at this stage. Finally, it is important to highlight that, despite of the fact that context-aware reasoning and case-based reasoning can be used together as complementing technologies to create intelligent environments, there are still several issues to address before the expected benefits are delivered. One of them is the formalisation of methodologies targeted to enhance the application of context-awareness together with case-based reasoning in intelligent environments. Another one is the integration of both concepts in more comprehensive systems implementing services that use case-based reasoning and others that do not use case-based reasoning in their logic. Finally, the application of both concepts in an intelligent environment real life scenario has not been studied yet.

Chapter 3

Methodology

This chapter describes the methodology that guided the research project. The User-Centric Intelligent Environment Development Process (U-CIEDP) is highlighted as the core of the methodology. The activities that led to obtaining the outcomes of the research project are explained under the framework of the U-CIEDP. Section 3.1 provides an explanation of the U-CIEDP, and how it guided the methodology of the research project. The foundations of the U-CIEDP and the scenario mapping its application in this research project are described. The description is given in the form of an incremental process focusing on linking the experiments that were done to the main components of the proposal of this research project.

The experiments that were done as part of the research project are divided into two groups: the initial stage project experiments and the final stage project experiments. The experiments are explained under the framework of the U-CIEDP in section 3.1. The details of the initial stage experiments are given in section 3.2 where the outcomes of these experiments are presented. The details and outcomes of the final stage experiments are presented in other chapters of the thesis (chapters 4 and 5), where the technology that is proposed and validated through these experiments is properly explained in order to understand the outcomes of these experiments better.

3.1 The User-Centric Intelligent Environment Development Process

The research project followed the U-CIEDP, which focuses on ensuring that the technology to develop offers services that closely match the requirements of users. It does not only consider the software component but also hardware, networks and interfaces, in order to make them interact in a way that satisfies users' expectations. The overall recipe for success of the U-CIEDP is acknowledging the human factor as the most influential one through the whole development of technology. An example of its application in the POSEIDON (PersOnalised Smart Environment to increase Inclusion of people with DOwn's syNdrome) project is shown in Ref. [15], which illustrates how the U-CIEDP was used to guide the development of smart technology for people with special needs. Chin et al. [32] recognise the U-CIEDP as a tool that also aids to ensuring technology in a morally and ethically responsible way.

The methodology of the research project under the framework of the U-CIEDP is shown in Fig. 3.1, which illustrates how the incremental contributions of the project were achieved through the involvement of the key stakeholders of the asthma management process. The research project considers people with asthma and their health carers (professional and non-professional) as the main stakeholders of the asthma management process. Hence, they have been included during the whole project in order to gather their main insights about the proposal of this research project. The circle tagged as *Stakeholders engagement* wraps all the activities that included interaction with the stakeholders of the asthma management process. The circle *Scoping* refers to the gaps that were spotted from the outcomes of the experiments. The analysis of these outcomes led to the development of ADAPT that is properly explained in chapter 4. The *Main development* circle refer to the components that were developed and then added to the prototype (*Installation* circle) that was used in the validation of the proposal. All the experiments that were done as part of the research project had the approval of the Computer Science Research Ethics Committee of Middlesex University.

The experiments of the research project are divided into two groups. The initial stage experiments group includes the *Literature survey*, *Interviews* and the *Personalisation questionnaire*. These experiments are considered part of the initial stage because their outcomes defined the path to follow considering the necessities of the main stakeholders of the asthma management process and the gaps of the existing technology supporting asthma management. The final stage experiments group includes the *Asthma Control Assessment Component (ACAC) validation*, the *Evaluation of using context-awareness together with case-based reasoning in a real scenario*, the *Virtual assistant (VA) questionnaire*, the *validation of ADAPT*, and one experiment that is not explicitly

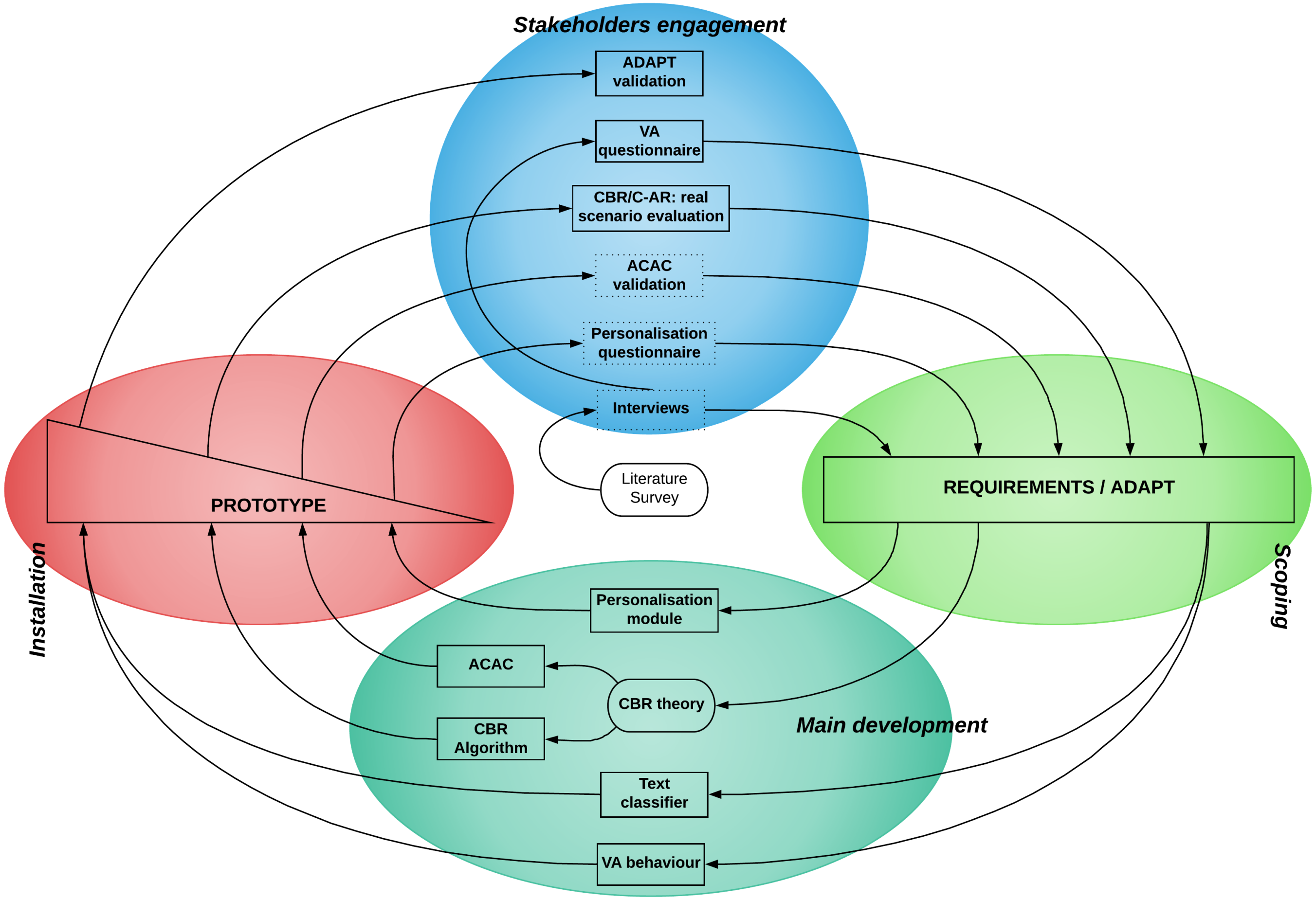

Figure 3.1: Methodology process of the research project under the U-CIEDP

shown in Fig. 3.1. This experiment is the *Synthetic evaluation of the case-based reasoning algorithm*. It is considered part of the development of the *CBR Algorithm* that is under the scope of the *Main development* circle.

The *Interviews* were defined based on the *Literature survey* studying existing context-aware solutions for asthma condition management. This initial literature review is mainly reported in section 2.1. The *Interviews* were thought as the mean to gather the insights of the stakeholders on the subject of using context-awareness in the management of their asthma. At this point, interviews was the research method chosen over the application of a questionnaire because the concept of context-awareness was considered complex enough to be explained through a questionnaire to people that is not familiar with computer science topics. This was thought as a risk that could be avoided by choosing the interview as the research method at this stage. Hence, the interviews provided the participants with a *"down to earth"* explanation of context-awareness, before asking them how it could be used to improve the management of their asthma. Four (4) people with asthma, two (2) non-professional carers of people with asthma, and one (1) expert in respiratory conditions were interviewed. The outcomes of this experiment are shown in section 3.2.

The experiment involving the *Personalisation questionnaire* was done in collaboration with Asthma UK through its Centre for Applied Research [13]. The main research interest of this research centre is addressing the main challenge of asthma applied research, which is preventing asthma attacks and asthma deaths. The questionnaire was created based on the outcomes of the interviews that provided insights about how to better formulate the questions in order to make them understandable enough for the participants. The main goal of this experiment was to collect the features that the stakeholders would like from a context-aware solution. The questionnaire was spread through the Patient Advisory Group of Asthma UK [14], which is a group of people with asthma, parents and carers of people with asthma that offer expertise based on their experience of living with asthma. The group includes over 120 people and 42 responses were gathered for the *Personalisation questionnaire*. The outcomes of this experiment are shown in section 3.2.

The *Literature survey*, *Interviews* and *Personalisation questionnaire* highlighted the necessity of providing technology facilitating the personalisation of the asthma management process. The outcomes of the *Literature survey* and the *Interviews* led to the development of the first version of ADAPT. This first version was implemented in the first module of the prototype, which is called the *Personalisation module*. ADAPT has substantially evolved since then, and its evolution and final version are thoroughly explained in chapter 4. The initial stage experiments also highlighted that people with asthma and their carers go through a very difficult time during the uncertainty stage, which is the stage when people with asthma do not know their triggers properly enough to being able to define a preventive strategy.

The *Personalisation module* that was built based on the first version of ADAPT could not provide support during the uncertainty stage. However, the interaction of context-awareness and case-based reasoning was expected to being able to provide stakeholders with support at this stage. For this, the *Literature survey* was expanded in order to know the possibilities of using both concepts at this stage of the condition. This expansion of the literature review, which is reported in sections 2.2 and 2.3, showed that despite of the potential benefits of using context-awareness together with case-based reasoning in the development of intelligent environments [56], no enough research has been done on studying and formalising their interaction in intelligent environments. Furthermore, it was found that this interaction had never been tested using data collected from users and in real life scenario (see section 2.3).

The theory of using context-awareness together with case-based reasoning for personalised asthma management was developed after the *Personalisation module* as a way to provide support in the uncertainty stage. The benefits and challenges of using both concepts together to address the uncertainty stage were spotted, and the algorithm adapting the case-based reasoning cycle for personalised asthma management was proposed. The case-based reasoning cycle for personalised asthma management is thoroughly explained in chapter 4, section 4.3.1. This algorithm was initially evaluated with synthetic data, before doing its evaluation with data from users in a real life setting. In order to evaluate the interaction of both concepts in a real life setting it was necessary to address one of the challenges spotted in the development of the theory of using context-awareness together with case-based reasoning for personalised asthma management. This challenge is about determining the real asthma health status of a person, which is highly important to complete the case-based reasoning cycle adapted for personalised asthma management.

The Asthma Control Assessment Component (ACAC) was developed and added to the prototype as the tool that is used to determining whether someone's asthma health status is deteriorated or not. The ACAC is important because it is thought to be used by real people with asthma in the experiment done to evaluate the use of context-awareness together with case-based reasoning in a real life scenario. Because of this, it was considered appropriate to assess the ACAC from a usability perspective as a midle step between the development of the theory and its evaluation in a real life scenario. This assessment had the aim of improving the ACAC in order to ensuring that people will use it properly in the real life scenario evaluation. Thus, the *ACAC validation* was done through an experiment involving real users who assessed the usability of the component and provided feedback to improve it. The experiment involved four (4) people with asthma and five (5) non-professional carers of people with asthma. They used the ACAC and, then, answered a questionnaire that was based on the Health IT Evaluation Model [27]. The outcomes of this experiment and the improvements that were done to the ACAC based on these outcomes are presented in chapter 4, section 4.3.3.

The evaluation of using context-awareness and case-based reasoning together for personalised asthma management was done in two phases. The first one was through a synthetic evaluation that used historical environmental data and asthma guidelines to create the cases and assess the effectiveness of using the case-based reasoning cycle to make predictions based on these cases. This experiment is more thoroughly explained in secion 4.3.2. The outcomes of this experiment supported the idea of using case-based reasoning together with context-awareness to provide support in the uncertainty stage. Thus, the second phase evaluated the use of both concepts in a real scenario. This was done through an experiment involving three (3) people with asthma. They used a version of the prototype that was adapted for it to being able to collect their environmental exposure during the day and their asthma health status (through the ACAC). They were asked to use the prototype for two months. The prototype did not implement the service of delivering alerts based on predictions because of ethical reasons. It is known that stress worsens or is a trigger of asthma attacks for some people, so delivering alerts was discarded in order to avoid false positives that could stress the participants and put them in situations that may affect their health. More details and the outcomes of the experiment are shown and analysed in section 4.3.3.

The study of virtual assistant as a complementary technology facilitating the daily activities of people affected by asthma is also considered by ADAPT. The people interviewed in the initial stage showed interest in exploring the use of virtual assistant technology to support their asthma management. The *Lit-*

erature survey supports this by showing that the application of this technology in asthma management has not been studied yet. The examples given by the interviewees show that they would use a virtual assistant in preventive and reactive situations. Moreover, although the usability validation of the ACAC did not include any specific questions about virtual assistant technology, some respondents suggested to use it as a complementary technology facilitating the detection of someone's asthma health status. This research project studies this technology through the case study of a virtual assistant that can be used as an alternative to the ACAC. This means that it can interpret a voice command said by the user, and determine if their asthma health status is normal or deteriorated by classifying the phrase said by the user. This outcome is stored as a record of their asthma health status.

The text classifier is the core element of the virtual assistant that is evaluated in this research work. It assesses if a phrase said by the person with asthma represents *"normal"* or *"deteriorated"* health status. The text classifier was trained using classification algorithms from scikit-learn, which is a machine learning library for Python [83]. The training was based on a set of phrases representing normal and deteriorated health status. These phrases were generated using keywords that were obtained from the *Interviews* and the most common reported symptoms from the *Personalisation questionnaire*. The experiment to evaluate the text classifier accuracy involved people with asthma through a questionnaire that asked for the phrases they would use to tell the virtual assistant that they feel well or bad as regards to their asthma. The questionnaire was again spread in collaboration with Asthma UK through their Patient Advisory Group. 107 phrases were collected from 18 respondents. More details of this experiment and its outcomes are shown in section 4.4.

Following the U-CIEDP, the validation of ADAPT, including all the components previously described, was done involving real users. They attended to an individual session in which the demonstration of a mobile application that was implemented using ADAPT was done. The participants were then asked to provide their insights about the proposal through a questionnaire that was made of open and closed questions. Ten (10) participants took part in the experiment. They were contacted through the Patient Advisory Group of Asthma UK. More information of this experiment is provided in chapter 5.

Evidence showing the bulletins spread by Asthma UK for the experiments in which they were involved and the flyers that were circulated for the experiments in which Asthma UK was not involved can be found in Ref. [90].

Moreover, photos of the experiments that were done to assess the usability of the ACAC and to validate ADAPT can be found in Appendix F or Ref. [91].

3.2 Initial stage experiments

The initial stage is made of the *Interviews* that were influenced by the initial *Literature survey* that studied the existing context-aware solutions for asthma management, and the *Personalised questionnaire* that was also designed considering the outcomes of the *Interviews* and the *Literature survey.* This section provides more details about these experiments and shows their outcomes.

3.2.1 Interviews

This experiment aimed at gathering insights about the potential benefits and challenges of using context-awareness to support the asthma management process. The questions guiding the interviews were defined based on the following points that explain some of the gaps that were found in the *Literature review*:

- *Personalisation*: None of the solutions allows users to set up the indicators they need to track according to the characteristic of their asthma.
- *Notifications*: The notification components of the reviewed solutions do not consider all the relevant stakeholders in the asthma management process of a person with asthma.
- *Location*: Solutions do not take advantage of the location-tracking capabilities of the integration devices.
- *Virtual assistant technology*: The use of virtual assistant technology to support the asthma management process has not been studied.

The questionnaire guiding the *Interviews*, which can be found in Appendix A or Ref. [93], is divided into five (5) groups of questions. The first group asked about more general questions aiming to classify the interviewees and finding out what practice they consider as good or bad to manage their asthma. The goal of asking about these practices is to know about the asthma-related habits a solution should help to enhance (good practices) and avoid (bad practices) in order to support asthma management.

The questions of the second group intend to gather their insights about using context-awareness to support their asthma management, define the indicators they consider should frame the health context of a person with asthma, and know the people they would like to grant access to their health context. An explanation of context-awareness through a presentation that included some application examples was provided to the interviewees before asking these questions.

The third group includes questions aiming to know what they think about using virtual assistant technology to support the management of their asthma, the situations in which they would use this technology, questions they would ask to a virtual assistant, and things they would expect to be told by the virtual assistant that are related to the management of their asthma. They received an explanation of this technology before answering these questions.

The questions of the fourth group were related to the notification component of a solution supporting asthma management. These questions intend to know some characteristics of the notifications they would like from a context-aware solution supporting the management of their asthma. The concept of notification was explained before asking the questions that aimed at knowing what notifications they would like to receive, the people they would like to include as recipients of notifications, and who they would like to contact in case of an asthma attack or imminent respiratory arrest.

The fifth group of questions asked about the interviewees perceptions about how the technologies that were discussed during the interview could benefit carers of people with asthma, and the negative effects that using these concepts could bring to the management of their condition. Some of these questions were implicitly answered before when the previous groups of questions were asked. Nevertheless, it was considered important to ask these questions explicitly at the end of the interviews as a way to gather more details about their thoughts related to the technologies that were discussed during the interviews.

The analysis of the interviews highlighted the following points:

1. *Personalisation:*

   Interviewees perceive that context-aware solutions can be used to achieve the personalisation of their asthma plans. They provide examples of using this kind of solutions in preventive and reactive situations. The preventive ones were more linked to being aware of the triggers and symptoms of the person with asthma, while the reactive ones mostly referred to being able to get help when they have an attack.

   They consider their contexts as changing and that their contexts depend on factors that are not only related to health. They stated that the people they would like to grant access or contact in case of emergencies are also part of their context and that the identity of these people change over time. For instance, a child would include their parents, and a adult person would include their partner as part of their asthma management process.

The context considered by them as health-related was thought as useful to define personalised reports about possible dangers that may be at the places they usually frequent. Moreover, having a record of their exposure is considered as a tool that could help people with asthma when they are discovering their triggers. They expressed that knowing what they were exposed to when they had an asthma attack would be very helpful.

2. *Notifications*

   Notifications are thought as a key service that a solution monitoring their context should offer. They expressed that regular notifications are useful in preventive situations but may not be effective in emergencies. They would like the system to make automatic calls and send messages automatically through SMS and other messaging services, like WhatsApp, when they are having an emergency. The anecdotes that were told by the participants when they answered the questions related to this point, mostly recalled asthma attacks that occurred during the first year from when they were diagnosed with asthma.

   They showed a high concern about dealing with their condition when they did not discovered their triggers yet, and about discovering what substances and situations made them having asthma attacks. Inclusion of professional healthcarers as recipients of information is also considered as an important service, especially when a person with asthma does not know their triggers properly. Being able to communicate and get feedback from their professional carers during this uncertainty stage was mentioned as positive.

3. *Location*

   Location is perceived as useful in preventive and emergency situations. It can be used to alert about the potential hazards that are nearby a person with asthma. It can also be used to create an historical record of the exposure of a person that can be reviewed when they have an exacerbation. The expert in respiratory conditions that was interviewed explained that being able to know where and when people with asthma use their emergency inhalers could be very beneficial, especially for research purposes.

The location of a person with asthma when they are in an emergency situation was considered as something that should be shared with their emergency contacts. This is thought as a life-saving feature a solution supporting people with asthma shall implement. It is important to highlight that this answer may have been influenced by one of the examples (PulsePoint [89]) shown in the explanation of context-awareness, which is a mobile application allowing people suffering heart attacks to share their location for being able to be found by people trained to assist them in these situations.

4. *Virtual assistant technology:*

   Virtual assistant technology was considered as less urgent to implement by the interviewees. Most of them agree that it is important to explore this technology because they perceive that people are using it more often. Nevertheless, only one of the interviewees claimed to use this technology as part of their everyday routine.

   The desired functionalities from a virtual assistant supporting asthma management can be also classified into preventive and reactive. Among the preventive ones, interviewees would like to use a virtual assistant to keep record of their health status. They would also like to ask the virtual assistant questions about potential hazards considering their triggers and the exposure at some specific places of interests. The reactive ones are about asking the virtual assistant to reach their emergency contacts. Carers said that they would like the virtual assistant to automatically tell them when those that they take care of are having an asthma attack.

The interviewees showed a good reception of the technology that was discussed in the interview. It can be said that context-aware solutions were perceived as a technology with the potential to provide support to asthma management in preventive and reactive situations. It was also recognised as a technology that can enhance good practice and help to avoid bad practice leading to deterioration in the health status of people with asthma.

Potential negative effects about using the technology were also spotted during the interviews. One of them refers to making people more dependant to the technology and lazy to learn about how to manage their condition by themselves, which makes them vulnerable when they do not have the technological support. Another is about the privacy and security issues, putting a special focus on who would access their data, how protected the data would be, and how the virtual assistant will know that it does not have to say anything about their condition when the person with asthma is surrounded by people they do not want to share information about their asthma with. Issuing false alarms and overloading users with too many notifications were also expressed as important concerns to consider in the design of the solutions.

3.2.2 Personalisation questionnaire

The *Personalisation questionnaire* had the aim of finding out the desired features/services that a context-aware system should offer in order to support asthma management in a personalised way. The outcomes of the *Interviews* helped to write the questionnaire by providing insights on how the stakeholders of the asthma management process would understand better some concepts. The *Interviews* reflected that an appropriate way of explaining a context-aware solution supporting asthma management was through the example of a mobile application, which is considered a technology that nowadays is well-known by people. Hence, the questions of this experiment are explained by referring to the features/services that a mobile application supporting personalised asthma management should provide.

The questionnaire is made of 18 questions and was applied to 42 people. The two versions of the questionnaire that were written (one for people with asthma and one for carers) can be found in Appendix B or Ref. [94]. The first six questions gathered general information about the characteristics of the respondents' asthma or the asthma of the person the respondents take (or took) care of, depending on whether the respondent is a person with asthma or a carer. Tables 3.1 and 3.2 show the options that were chosen by the respondents as regards to their triggers and symptoms. These tables report on the answers for Question 5 and Question 6 by showing how many respondents chose each of the triggers and symptoms listed in those questions. The tables also show the percentage that those numbers represent from all the 42 respondents. The rows of these tables are sorted in descending order by the number of respondents that chose each trigger and symptom. The other questions are explained below along with the presentation of its outcomes.

Table 3.1: Triggers ordered by number of respondents (Q5)

	Trigger	# respondents	%
1	Dust	30	71.43
2	A cold	29	69.05
3	Flu	23	54.76
4	Cigarette smoke	22	52.38
5	Exercise	22	52.38
6	Air pollution	21	50.00
7	House dust mites	20	47.62
8	Pollen	20	47.62
9	Damp (humid) weather	20	47.62
10	Cold weather	19	45.24
11	Poor indoor ventilation	18	42.86
12	Cleaning products	17	40.48
13	Mould	17	40.48
14	Animals fur/feathers	16	38.10
15	Sudden temperature changes	15	35.71
16	Stress or anxiety	14	33.33
17	Open fires	13	30.95
18	Strong emotions	10	23.81
19	Products used for decoration	10	23.81
20	Hot weather	9	21.43
21	Carpets	8	19.05
22	Dry weather	7	16.67
23	Food	7	16.67
24	Fungi	5	11.90
25	Alcoholic drinks	5	11.90
26	Furniture	2	4.76
27	Cockroaches	1	2.38

Table 3.2: Symptoms ordered by number of respondents (Q6)

	Symptom	# respondents	%
1	Shortness of breath	35	83.33
2	Wheezing	32	76.19
3	Coughing	31	73.81
4	Tightness in the chest	28	66.67
5	Throat feels scratchy	18	42.86
6	Breathing faster	16	38.10
7	Being too breathless to eat, speak or sleep	16	38.10
8	Rapid heartbeat	14	33.33
9	Nose feels scratchy	14	33.33
10	Drowsiness	7	16.67
11	Blue lips or fingers	5	11.90
12	Dizziness	3	7.14
13	Confusion	2	4.76
14	Fainting	1	2.38

Question 7 asks for the physiological indicators the person with asthma would like to monitor. The answers to this question are summarised in Fig. 3.2, which shows the number of respondents that chose each of the indicators listed in Question 7. Some of them suggested other indicators that were not listed in the question, like *"monthly cycle for women", "peak flow", "lung function", "coughing", and "waking at night".*

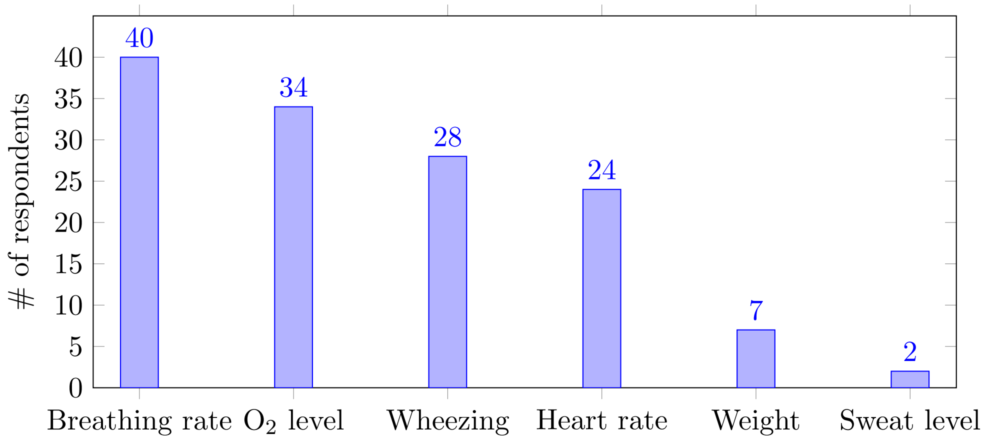

Figure 3.2: Physiological indicators (Q7)

Questions 8 and 9 asked about the indoor and outdoor environmental indicators, respectively, that the respondents consider the mobile application should monitor. The answers to this questions are summarised in Fig. 3.3 and 3.4. Two respondents suggested something in the option other for Question 8. One stated *"not being sure if any of the answers presented as options [in the question] apply to them"*. The other respondent wanted to monitor *"allergens such as pollen and cat hair"* as indoor environmental indicators. The other options suggested by the respondents for Question 9 are *"wind speed because if it is dry and windy the environment creates a lot of dust* and *"cigarrete smoke"*.

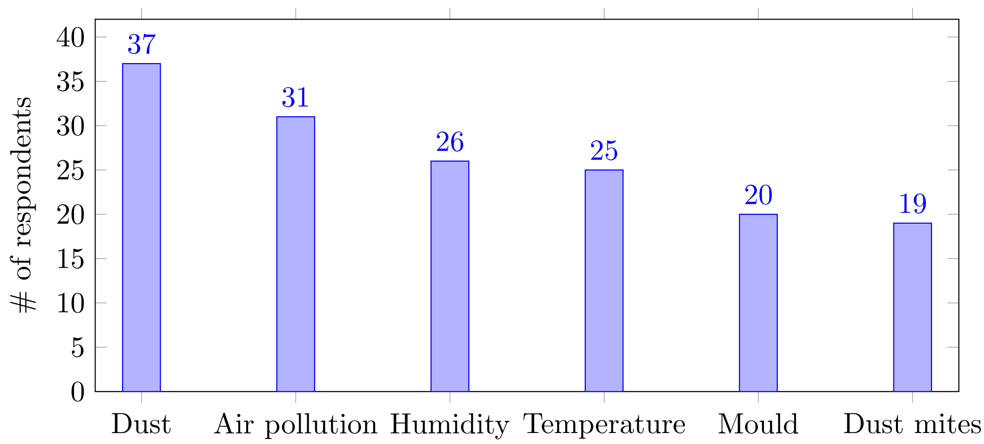

Figure 3.3: Indoor environmental indicators (Q8)

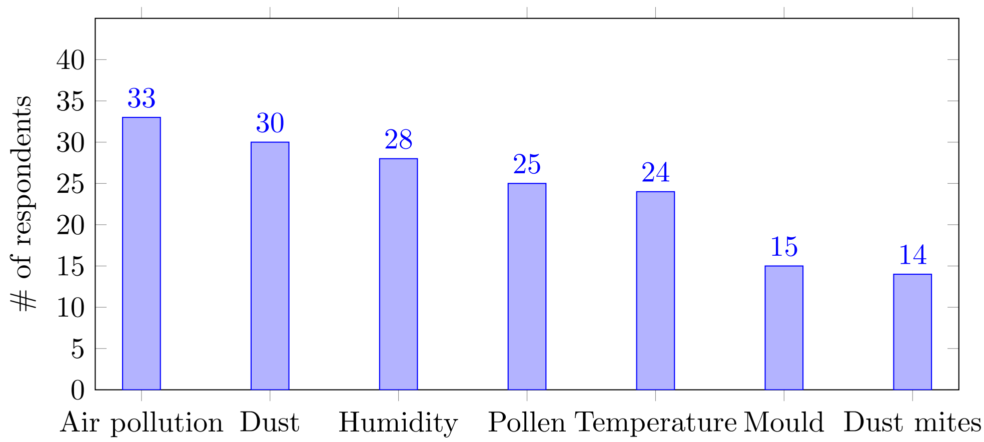

Figure 3.4: Outdoor environmental indicators (Q9)

Question 10 asks about to whom the respondents would grant access to the information collected by the mobile application. Figure 3.5 summarises the answers for this question. Other options were also suggested by the respondents. One of them suggested that *"anyone who I think would benefit from the information"* should be granted with this privilege. Another one supported this by stating that the mobile application should *"give choice on access to the patient"*. A respondent also suggested to give access to *"a trusted friend of their daughter because s/he is a widowed and lives alone"*. Finally, another one said they would like their *"brother to have access"*.

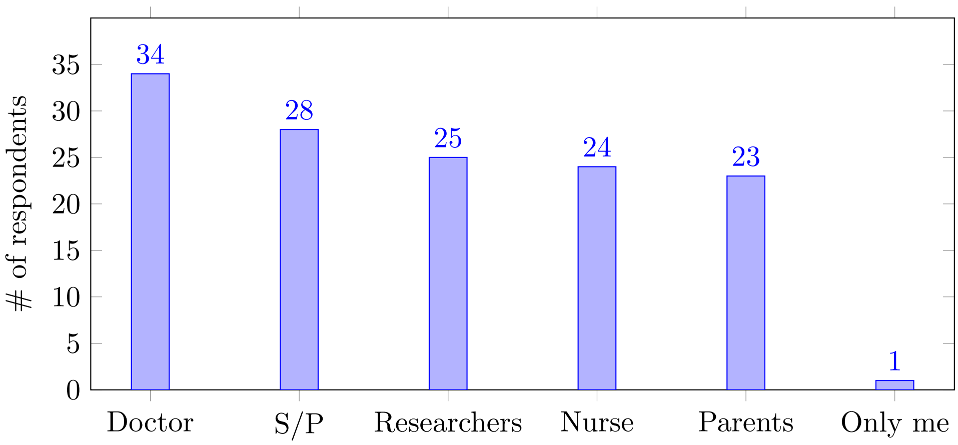

Figure 3.5: Who to give access to the information collected? (Q10)
S/P: Spouse or partner

Question 11 asks respondents to rate some features/services a mobile application supporting asthma management should offer. Most of these services were proposed by the interviewees in the previous experiment. The answers to Question 11 are summarised in Fig. 3.6-3.8, where the features of a context-aware solutions supporting asthma management are rated from 0 (non-important) to 5 (most important). Question 12 is also related to this topic as it asks for other features that are not listed in the question and the respondents would like to have. Some respondents suggested the following by answering to Question 12: *"adherence monitoring"*, *"reminders when there is a good day"*, *"alert emergency centre staff in case of emergency"*, *"peak flow diary facility"*, *"nutritional support"*, *"a guide on how to act in case of emergency"*, *"a guide to use inhalers correctly"*, *"monitoring signs and symptoms"*, *"saving details of the last asthma occurrence"*, *"nearest and cheapest place to get medicine"*, *and "alerting when my inhaler is going to run out"*.

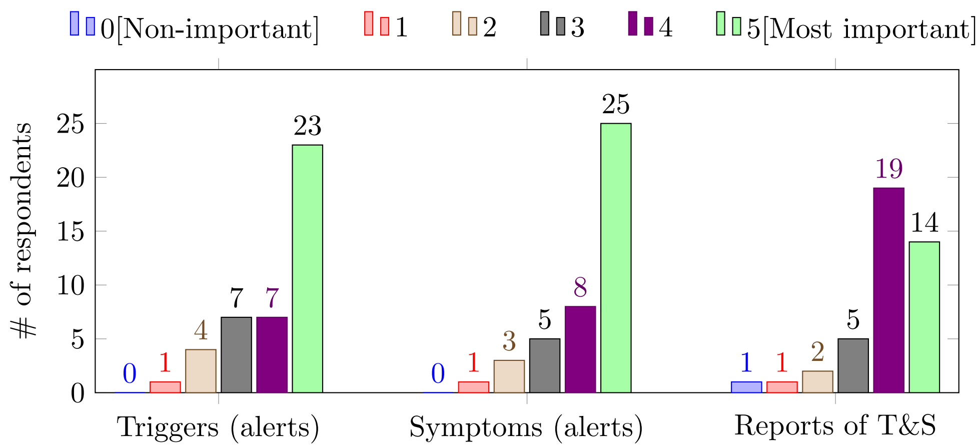

Figure 3.6: Features of solutions supporting asthma management - a (Q11)

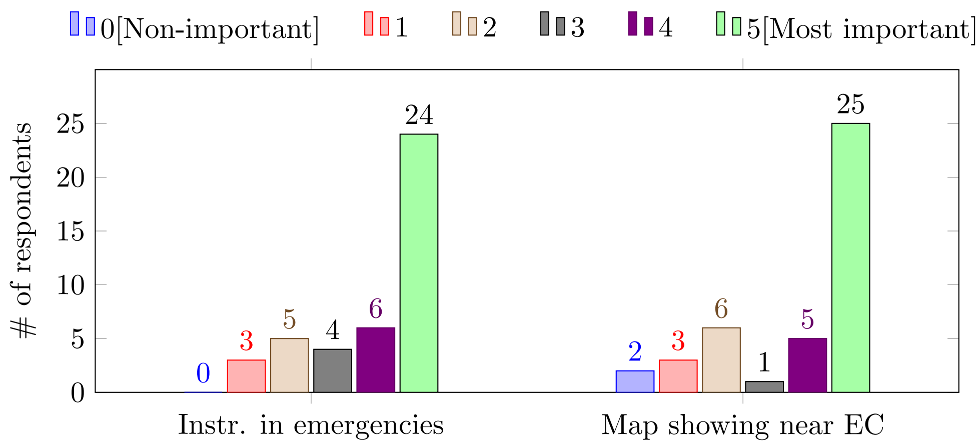

Figure 3.7: Features of solutions supporting asthma management - b (Q11)

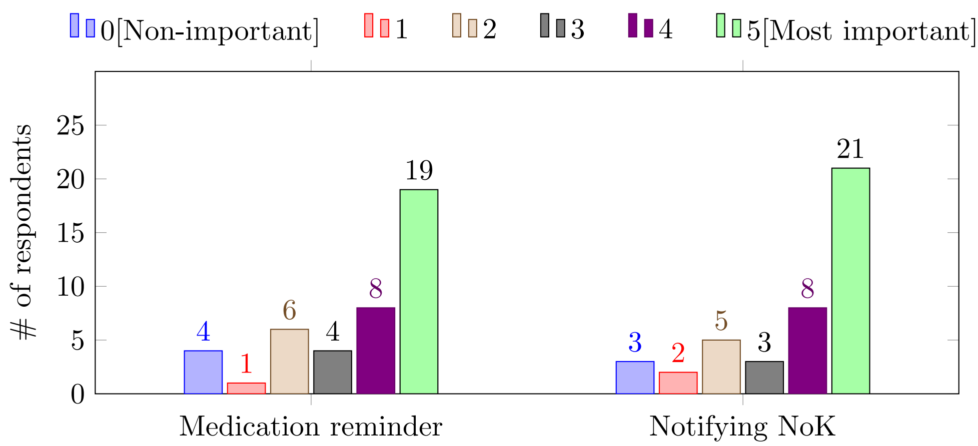

Figure 3.8: Features of solutions supporting asthma management - c (Q11)

Question 13 asks for the people/institutions the respondents would like to include as recipients of notifications of a mobile application supporting the management of their asthma. The answers are summarised in Fig. 3.9.

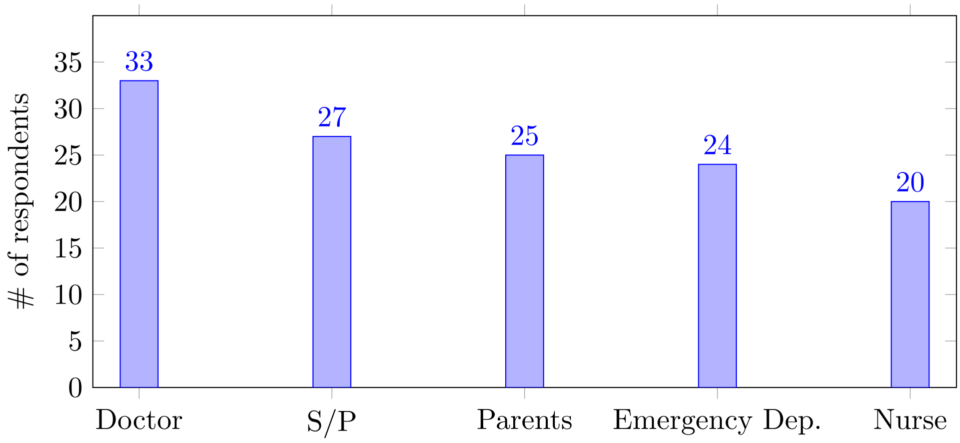

Figure 3.9: Who should receive notifications? (Q13)
S/P: Spouse or partner

Question 14 asks about who the respondents would like to contact in case of an asthma attack or imminent respiratory arrest, and how they would like to contact them. The answers to this question are summarised in Fig. 3.10. Question 15 is also related to this topic by asking who else that is not listed in Question 14 they would like to contact in case of an asthma attack or imminent respiratory arrest. The answers to Question 15 were: *"general practitioners, emergency services, next of kin, doctor, nearest A&E centre, close friend, and work colleagues"*.

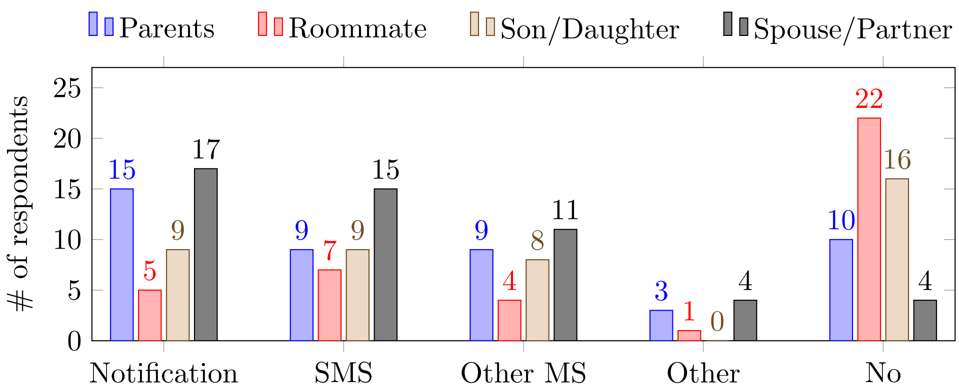

Figure 3.10: Who and how to contact in case of an AA/RA? (Q14)
AA/RA: asthma attack or respiratory arrest

Question 16 asks about what information the respondents would like to send to those chosen in Question 15 in case of an asthma attack or imminent respiratory arrest. Figure 3.11 summarises the answers to this question. Only one respondent chose the option other for Question 16, stating they would also like to send *"information about their allergies, like Penicillin"*.

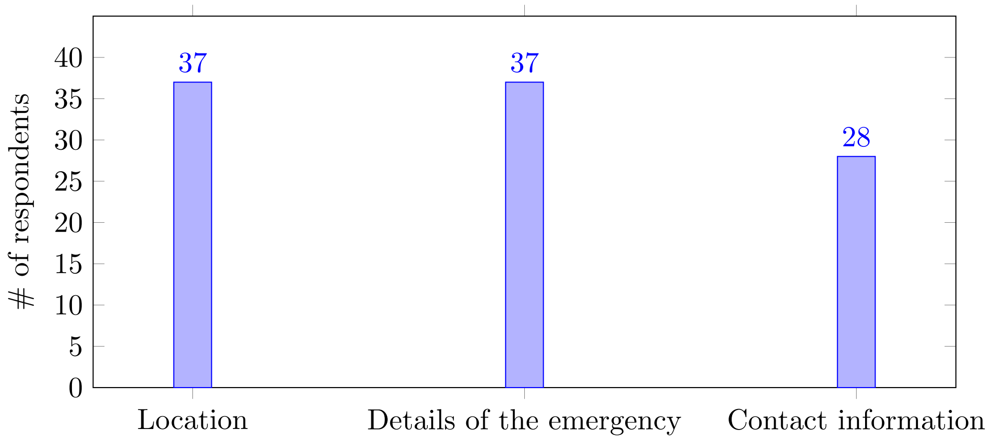

Figure 3.11: What to send in case of an AA/RA? (Q16)
AA/RA: asthma attack or respiratory arrest

Question 17 asks about the benefits that using a mobile application offering the features discussed throughout the questionnaire may bring. The answers of the respondents for this question are summarised in the following points:

- It will help people with asthma and their carers to have a better quality of life.
- It will help to have a better understanding of someone's asthma and make more informed decisions.
- It will help to reduce the number of deaths from asthma by making people able to react faster and better to emergencies.
- The collected data will help people doing research on the topic.
- It can be used to anticipate dangers that may lead to asthma attacks.
- It will facilitate the communication with doctors and nurses.
- The technology will allow people with asthma to keep it up with the real world.
- It may improve efficiency of staff.

- It will aid to find the right treatment.

Question 18 ask about the negative effect that using a mobile application offering the features/services discusses throughout the questionnaire may bring. The answers of the respondents to this question are summarised in the following points:

- The portability of the devices that will monitor some indicators is a concern.
- People might get tired of the system and start ignoring it.
- Security and privacy of the data collected through the system is very important for the users.
- False positives and delay in delivering relevant information are concerns that may lead to make people stop using this technology.
- Stress and anxiety should be taken into account because they may be triggers for some people with asthma.
- It could make people lazy to learn and understand their condition better.
- Avoid dependency because people should know how to act even without this technology.
- Information overload will make people stop using it.

The variety of the indicators the respondents wish to monitor is high (see Fig. 3.2, Fig.3.3 and Fig.3.4). This can be considered as evidence re-confirming the necessity of having monitoring process that are able to adapt the specific characteristics of someone's asthma. This variety of indicators is noticeable even for individual answers referring to the indicators to monitor for indoor and outdoor environments. Some respondents chose to monitor indoor environmental indicators that were different from the outdoor environmental indicators they chose to monitor.

The people that were chosen to be granted with access to the collected data is different from person to person. Fig. 3.5 shows that most of the respondents would like to give access to their doctors. The number of respondents that chose to give access to their Spouse/Partner (28), Nurse (24), Parents (23), and Researchers (25) can be considered as similar. This similarity is also evidence that this choice depends on the specific situation of a person with asthma. It is important to highlight that only one respondent chose not to grant access to this information to anyone.

The features assessment that is summarised in Fig. 3.6, Fig. 3.7 and Fig. 3.8 shows that all the choices that were suggested to the respondents were assessed with the two highest possible values (4 or 5) by between 67% and 79% of the respondents. Some of these features were also evaluated with very low values, which means that some people would not use some of the suggested features in case they were available. The variation in these results is considered to be a consequence of the personal preferences of each participants.

The people/institutions that were chosen to be notified are also different for each participant (Fig. 3.9). Although doctors are those that were chosen the most as recipients of notifications, it might not be convenient to overload doctors with notifications from the people they treat. This logic could also be applied for those that chose their nurses as recipients of notifications. In order to achieve this, the type of notifications that will be delivered to each of those chosen as recipients of notifications should be carefully defined. A notification component of a solution using the technology described in the questionnaire should be flexible.

The people to contact and how to contact them in case of an asthma attack/respiratory arrest (Fig. 3.10) are also answers showing that respondents would like to personalise these choices. Spouse/partner was the option that was chosen the most by the respondents. The way of contacting them is also different depending on the participants but the option *Notification on their phones* is the one that was chosen the most. About the information to send in case of an asthma attack/respiratory arrest (Fig. 3.11), *Location* and *Details of the emergency* were chosen by 88% of the participants. *Contact information* was chosen by 67% of them.

3.3 Chapter summary

This chapter presented the methodology that was followed to achieve the aims and objectives of the research project. The methodology is based on the U-CIEDP and, thus, the main stakeholders of the asthma management process were involved in several stages of the research project. The research tools that were used in the experiments of the research project and the logic for choosing these tools were explained. The collaboration with Asthma UK was highlighted as the key element of the methodology that allowed to involve people with asthma, professional and non-professional carers of people with asthma, and experts in respiratory conditions in the scoping and validation stages of the research project. The initial stage experiments were those that defined the scope of the research project. The outcomes of these experiments were presented, as well as how these outcomes aided in the definition of the scope of the research project.

Chapter 4

ADAPT: Approach to Develop Context-Aware Solutions for Personalised Asthma Management

This chapter presents the Approach to Develop context-Aware solutions for Personalised asthma managemenT (ADAPT) that guides the development of context-aware solutions supporting personalised asthma management with the aim of addressing the high heterogeneity level of the condition.

The evolution of ADAPT, as a consequence of the interaction with the main stakeholders throughout the research project, is explained in section 4.1. The description is illustrated with the explanation of a diagram that represents how the high level architecture of a system that is built based on ADAPT would look like. The layers of this architecture system are explained putting a special emphasis on the one that allows its customisation.

Section 4.2 explains the context dimensions considered by ADAPT to allow the personalisation that is required to support asthma management. The explanation of the context dimensions are supported by practical examples of how each of them influences the customisation of a system built based on ADAPT. An application example describing how the approach can be used to characterise three real people with asthma is shown in section 4.2.1.

Section 4.3 presents the use of context-awareness together with case-based reasoning as a tool to provide support in the uncertainty stage of asthma management. For this, the case-based reasoning cycle adapted for asthma management is proposed (section 4.3.1) and synthetically evaluated (section 4.3.2). Then, a case study, in which real data from three people with asthma were collected and assessed using context-awareness together with case-based reasoning, is shown in section 4.3.3. Finally, the interaction between these two concepts as part of ADAPT is explained in section 4.3.4.

The study of virtual assistant as a complementing technology with the potential of enhancing the human-computer interaction of a solution supporting asthma management is shown in section 4.4. This study focuses on using virtual assistant as an alternative to the ACAC, which allows to determine the asthma health status of a person and complete the case-based reasoning cycle for asthma management.

4.1 Description of ADAPT

ADAPT has evolved as a natural consequence of using the U-CIEDP in several iterations. The interaction with the main stakeholders and the lessons learned from the execution of the research project have allowed to improve the approach. The first version of ADAPT suggested to allow users to choose the indicators to monitor and the places where they want to monitor these indicators considering the specific characteristics framing their condition. It also proposed to classify the indicators to monitor into three types: patients indicators, indoor environmental indicators and outdoor environmental indicators. This classification allows to monitor the context of a person with asthma in a more comprehensive way, and provides the basis for the application of more complex decision-making processes.

The first version of ADAPT was the first and a very important step towards the personalisation of asthma management using context-aware solutions. Before ADAPT, no efforts had been made on proposing technology addressing the personalisation that is required to undertake the high heterogeneity level of asthma. However, this version had to be improved for it to being able to guide the development of context-aware solutions that are able to provide support when there is a high level of uncertainty about the triggers of people with asthma (uncertainty stage). This means that, although the first version of ADAPT could be used to create solutions for people that know their triggers properly, it could not be used to create solutions helping those that poorly know or do not know their triggers.

The uncertainty stage is important to be addressed. The analysis of the interviews showed that people with asthma have a lot of difficulties during the first year from their diagnosis. This happens because they need to discover their triggers and gain knowledge about how to deal with them. Several of them also stated having gone through similar difficulties when they moved to other places (e.g. a different city) where they were exposed to new substances they had not been exposed before (see section 3.2.1). The expert in respiratory conditions that was interviewed also explained that the triggers of people with asthma might change over time, which is a statement also supported by Ref. [117]. When this happens, people with asthma go through this *"trial-and-error"* process in which they have to discover and gain knowledge about their new triggers again.

Case-based reasoning has been assessed as a suitable solution to address the challenge of the uncertainty stage as it can build knowledge from previous experiences in the form of cases that can be used to attempt the prediction of the health status of a person with asthma. This was added to ADAPT as a way of providing support to people with asthma that are in uncertainty stage. Case-based reasoning brings other interesting issues to address in the development of context-aware solutions for personalised asthma management. These are thoroughly explained in section 4.3.1.

Figure 4.1 shows a high level architecture diagram that aims at illustrating how ADAPT can be used to create solutions supporting personalised asthma management. The first version of ADAPT is mainly represented by the *Personalisation layer* that influences all the other layers of the system. The user interacts with the *Personalisation layer* in order to provide the system with their preferences about the indicators to monitor and where to monitor these indicators. It also allows to choose the people to contact and how to contact them in case of emergency. Thus, the *Personalisation layer* stores these preferences as a profile in the *Personalisation database* that will be then queried by the same layer in order to define the behaviour of all the other ones.

The overall system is influenced by the *Personalisation layer*. The *Data layer* collects the context-related data considering the profile built and delivered by the *Personalisation layer*. Thus, if the user chooses to monitor temperature and humidity at some specific places, the *Data layer* will then collect temperature and humidity data at those places of interest. The *Context layer* monitors and control the contextual data in real time considering the indicators the user defines to monitor through the *Personalisation layer*.

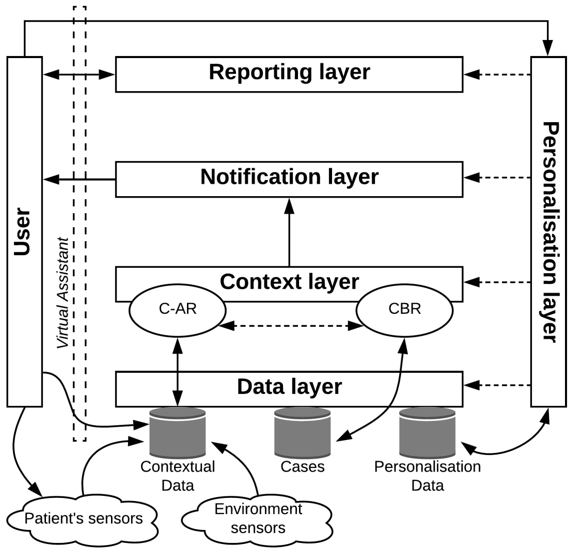

Figure 4.1: The high level architecture of a system built based on ADAPT

The *Notification layer* also performs according to the preferences of the user regarding what people to notify and how to notify them. Finally, the *Reporting layer* shows the status of the indicators the user chooses to monitor in their preferences. A deeper analysis of the context dimensions considered in the performance of the *Personalisation layer* is shown in section 4.2.

The use of case-based reasoning to support personalised asthma management in what it is called the uncertainty stage brought some improvements to ADAPT. One of them is the inclusion of the *CBR* component in the *Context layer*. The *C-AR* and *CBR* components complement each other to provide support in the uncertainty stage. The *C-AR* monitors the indicators at the places of interest in real time, and the *CBR* attempts the prediction of hazardous situations when the person does not know what indicators to monitor. The inclusion of the *CBR* also brings the need of having a database of *Cases* in the *Data layer*. The *C-AR* and *CBR* components also complement each other in the internal performance of the system. This complement is represented by the dotted two-headed arrow connecting the *C-AR* and *CBR* components. *C-AR* is very important when it comes to collect the context-related data the *CBR* uses to create the cases. On the other hand, when the *CBR* detects a hazardous situation, it also has to interact with the *C-AR* that provides the notifications to the user and other stakeholders that have been selected as recipients of information. A more detailed explanation about the interaction between the *C-AR* and *CBR* is provided in section 4.3.4.

The interaction with the stakeholders brought another interesting feature to include in ADAPT, which refers to the use of virtual assistant (VA) technology to support personalised asthma management. The initial interviews (see section 3.2.1) and the validation of the ACAC (see section 4.3.3) highlighted the possibility of developing a virtual assistant able to provide support to asthma-related matters. Although the assessment the ACAC by real users showed very positive results, some participants of this experiment also suggested to explore the use of virtual assistant technology as an alternative to provide information about how they feel at a specific time of the day.

The VA feature of the system is represented by the dotted rectangle placed between the *User* layer and the layers of the system in Fig. 4.1. It can be interpreted as an alternative way of communication with the system. The VA can be used to interact with the *Personalisation layer* by giving instructions to define their profile. The *Reporting* and *Notification* layers can also use the VA to give information to the *User*. Finally, the *User* can provide data to feed the *Contextual Data* database through sensors measuring their physiological indicators (like heart rate or oxygen level), using the ACAC to provide their health status, and through a VA that interprets how they are feeling based on the phrases they use to express this. ADAPT considers all these applications of VA for personalised asthma management. However, this research project explored the development and validation of a VA than can be used as an alternative to the ACAC for those users that would like to use a VA. This is presented in section 4.4.

4.2 Context dimensions for personalised asthma management

The performance of the *Personalisation layer* shown in Fig. 4.1 is based on the information that is considered as relevant by the user. This brings the question of what information the user should be able to manage in order to make their personalisation comprehensive enough for their asthma management process. This question has been considered throughout the whole research project, especially in those processes involving interaction with stakeholders. Hence, as an attempt to contribute to answering that question, this section reports on the improvements made to the context classification proposed in the first version of ADAPT. Figure 4.2 presents the context dimensions a solution shall

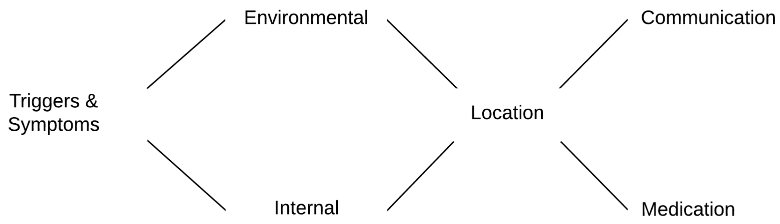

Figure 4.2: Context dimensions for personalised asthma management

be able to handle in order to provide the users with a suitable tool allowing a personalised management of their asthma. The strongest relationships among these dimensions are represented by the lines connecting them.

The importance of the *Triggers & Symptoms* is that they define what situations can lead a person to experience an exacerbation, and what this person feels when an exacerbation occurs. A list of 27 potential triggers and 14 potential symptoms can be made by collecting the information provided by organisations doing research on asthma [10, 12, 107, 108]. This usually makes the process of identifying the triggers and symptoms of a person with asthma to be a difficult task. Nevertheless, this identification is very important to achieve because it is the basis to define the proactive plans to avoid the triggers, and the reactive plans to follow when the symptoms appear. Hence, once the *Triggers & Symptoms* of a person are known, then it is possible to define the *Environmental* and *Internal* indicators that should be monitored.

The *Environmental* context dimension refers to the environmental indicators to be monitored considering the characteristics of someone's asthma. These indicators can be tracked at different indoor and outdoor places of interest of the person. These places are usually those that they frequent but they could include others, like places they know they will visit. Flexibility in choosing the indicators to monitor at each place should be allowed as not all the places of interest may have the same monitoring equipment available. For instance, a person allergic to pollen may want to monitor Particulate Matter 10 (PM10) levels at some parks they usually go, and this is possible to do at some outdoor places through APIs providing this information (like the London Air Quality Network API [58]). However, it is still not common to have devices monitoring PM10 at indoor places. The indicators that are available to monitor at the places of interest should be shown to the users for them to choose the most suitable monitoring configuration.

The control limits that are used to monitor different indoor and outdoor places of interests should also be defined by the user. These control limits might differ depending on the nature of the activities people do at those places. A simple example to clarify this is defining the lower control limit for temperature at indoors and outdoors. A person would like to be alerted when the outdoor temperature is below 10°C in order to wear appropriate clothes. However, the lower control limit for their home would be higher (e.g. 20°C) as people usually rather wearing lighter clothes at home for comfort, and they could adjust the temperature at indoors places like this. A solution supporting personalised asthma management should be flexible enough to adapt to these common situations.

Processing the data collected through monitoring devices or APIs is another important issue to consider for the *Environmental* indicators. Some metric units are globally known and there is no need to provide an interpretation for the conditions they represent. For instance, most people understand the metric units for temperature (°F or °C) and humidity (%), however, the metric unit that is used to measure PM2.5 and PM10 (ug/m^3) is less common. People usually do not understand what it means, and they cannot interpret the numbers of these measurements. Because of this, it is important to define how this information is shown to the user. Following the same example, one option is to show the air quality band (1-10) and its description (Low-Medium-High) for the measurements of PM2.5 and PM10. Nevertheless, choosing the right standard (e.g. the COMEAP standard for UK [33]) to define the air quality bands to use and its interpretation is another issue to deal with.

The *Internal* indicators mostly refer to physiological indicators such as heart rate, lung capacity, respiratory rate, among others. However, it also includes other more elaborated indicators like exercise activity level, stress level, and even the outcome of using a tool to determining their health status, like the Asthma Control Questionnaire (ACQ). An important characteristic of the *Internal* indicators is that, although most of them are associated with symptoms, some of them are related to triggers (e.g. stress level or exercise activity level). The processing of the data is also important for this type of indicators as the users should be able to understand what they mean. For instance, the raw outcome of the ACQ is a number whose interpretation (*normal or deteriorated* health status) should be shown to the user.

The *Location*, from a software development perspective, is the most relevant context dimension to handle because it makes possible to deliver most of the preventive features supporting personalised asthma management. Its relationship with the *Environmental* indicators is probably the strongest given the fact that ADAPT allows to monitor different places at the same time. Thus, it is critical for the solution to being able to established the current location of a person in order to warn them in case they are expose to hazardous environmental triggers. The relationship with the *Internal* indicators that evidence the appearance of symptoms is also important because knowing the places where a person usually shows symptoms can be useful in several situations. For instance, it could help to know if a person is monitoring the wrong indicators or the wrong places. The link of the *Location* dimension with the *Communication* and *Medication* dimensions is explained below where these last two dimensions are described.

The *Communication* dimension aims at allowing the stakeholders to being actively involved. Their involvement has been thought to provide support in preventive and reactive situations by classifying them considering their generic roles played in the asthma management process. A stakeholder could be granted with one or more of the following permissions that were defined based on the outcomes of the interviews and questionnaires applied to people with asthma and stakeholders:

- The *Check Status* permission allows the stakeholder to see the indicators that are linked to the health status of the person with asthma. It provides access to the *Reporting layer* shown in Fig. 4.1. This permission could be granted, for instance, to their nurse when they need to review health-related information.

- The stakeholders with *Notifications* authorisation will receive notifications when there is a potential hazard at the places of interest that are being monitored. Parents of children with asthma and adults taking care of elder people with asthma, for example, could be granted with this authorisation.

- Stakeholders with the *Emergency* permission will receive emergency ale–rts when the person confirms that they are having an asthma attack and deploys the emergency notification protocol. The teacher of a child with asthma at school times, and the roommate of a person with asthma that goes to college are examples of people that could be granted with this permission.

The relationship between *Communication* and *Location* is evident in reactive situations when the emergency notification protocol is deployed. The emergency alerts should show the current location of the person having an asthma attack for the stakeholders to being able to reach them. An issue to consider here is the way of sending notifications and emergency alerts to the stakeholders. For this, the IT literacy and preferences of the people to contact should be considered. Hence, the solution should allow to personalise how to reach the stakeholders automatically. Some options that came out from the interviews and the personalisation questionnaire are: SMS, other messaging service (e.g. WhatsApp), emails, notification on their smartphone, and even automatic calls.

The *Medication* dimension is thought to include the pharmacological strategy as part of the asthma management plan. People with asthma usually go through a stepwise approach until finding their optimal pharmacological treatment [107, 108]. This means that the pharmacological strategy of a person with asthma should also be personalised and, although there are mHealth applications providing services aiding medication management (see Ref. [106] as an example), it is important to consider the inclusion of this type of features in a solution supporting personalised asthma management. An obvious benefit of monitoring medication usage is that it can facilitate the adjustment of the pharmacological treatment of a person with asthma.

The relationship between *Location* and *Medication* is also very important to consider. The benefit of building this relationship was highlighted by the expert in respiratory conditions that was interviewed. This benefit refers to being able to know the places where people with asthma use their rescue inhaler (salbutamol) more frequently. The rescue inhaler is used when they have an exacerbation. Thus, it can be used as a good indicator to know the places where they usually feel unwell and, thus, monitor and warn about those places. It could also be used to suggest the user places of interest that should be included in the monitoring process.

Efforts on creating automatic counter inhalers have been made (e.g. see Ref. [121]), and even on linking these counter devices to the location where they are used (e.g. see Ref. [43]). Nevertheless, this research work proposes to use the *Medication* dimension in a more comprehensive way by associating it with the *Communication*, *Physiological* and *Environmental* dimensions through the *Location* one. By doing this, more meaningful information of the medication usage can be obtained for enhancing decision-making in asthma management.

4.2.1 Application example: Using ADAPT to describe a real case study

This section illustrates how ADAPT can be used to facilitate the personalisation of asthma management by using it to describe the context of three people with asthma. They are the participants of the experiment that is then reported in section 4.3.3, in which the use of context-awareness and case-based reasoning for personalised asthma management is evaluated in a real scenario.

The participants have been diagnosed with asthma and they have been dealing with this condition for a relevant time, so they know their condition properly. They will be referred to as *Person A*, *Person B* and *Person C*. They are 34, 36 and 26 years old, and they were diagnosed 8, 7 and 20 years ago, respectively. *Persons A and C* suffer from mild asthma, while *Person B*'s asthma is considered to be moderate. The data for this case study was collected through interviews.

The core of this case study is using the context dimensions proposed in ADAPT (see Fig. 4.2) to represent the contexts of the participants concerning their asthma management processes. This representation shows how a context-aware solution can use the approach to provide personalised services and fit users' needs better. Table 4.1 shows how ADAPT context dimensions shape the context of the three participants.

The use of ADAPT to represent the context of the participants shows that it is able to provide enough flexibility to describe the information that is relevant to their asthma management. The flexibility of ADAPT is evidenced in the description of the participants' *Trigers & Symptoms*, *Internal Indicators* and *Medication* dimensions in a less significant way than for the monitoring of *Environmental* places and the description of the *Communication* dimension. The *Location* dimension is not explicitly shown as it is a real time changing dimension, however, it is considered as the transversal layer making it possible to exploit the information described by the other context dimensions.

Table 4.1: Using ADAPT context dimensions to characterise the case study

		Person A	Person B	Person C
Triggers &		Temperature changes	Temperature changes, low temperatures, high humidity.	Demanding cardiovascular exercises
Symptoms		Coughing	Chest tightness, coughing, breathless	Chest tightness, coughing, wheezing
Environmental	House	Temperature	Temperature, humidity.	N/A
	Workplace	Temperature	Temperature, humidity.	N/A
	University	N/A	Temperature	N/A
	House area	Temperature	Temperature, humidity.	N/A
	Workplace area	Temperature	Temperature, humidity.	N/A
	University area	N/A	Temperature, humidity.	N/A
Internal		Asthma health status	Respiratory rate, weight, asthma health status.	Heart rate, respiratory rate.
Comm.	Check status	Parents	Wife	Sister
	Notifications	N/A	Wife	N/A
	Emergency	Parents	Wife	Sister, grandmother
Medication		Salbutamol in emergencies	Controller twice a day, salbutamol in emergencies.	Salbutamol in emergencies

The capability that ADAPT provides to monitor different indicators at different places of interest is one of the points to highlight from table 4.1. For instance, *Person B* chose to monitor indoor indicators at their University that are different from those that were chosen for their House and Workplace. *Person B* chose this because *"it is not possible to change the humidity level, even if it is too high, at the classrooms"*. Although it would be good for *Person B* to know the humidity level, they are also aware that it would be difficult to configure and monitor all the rooms where they receive lectures. Nevertheless, *Person B* considers relevant to monitor the outdoor humidity nearby the University area as it would be easier to do.

The *Communication* dimension of table 4.1 shows the people the participants would like to involve and how they would like them to be involved. This dimension also evidences the customisability that ADAPT allows to include the participants' stakeholders and the privileges that can be granted to them in their condition management. The approach considers that the stakeholders and their roles could change. This case study highlights this flexibility by showing how the participants have different roles and privileges granted to their stakeholders in their *Communication* dimensions.

4.3 Context-aware Reasoning and Case-based Reasoning for Personalised Asthma Management

Asthma management plans are made of strategies that aim at achieving control of the condition. Non-pharmacological strategies are related to taking preventive measures to avoid situations that may be dangerous for a person with asthma [107, 108]. For this, it is important to know the triggers provoking exacerbations in a person with asthma, which is very difficult to achieve given the high heterogeneity level of the condition. Moreover, even if the person gains enough knowledge about their triggers, there are still some situations in which they would go through similar difficulties again. A typical example of this type of situations is a person with asthma moving to a new city where they are exposed to substances they were not exposed before. When this happens, people with asthma shall go again through the trial-and-error process of guessing what new substances are those that are affecting their asthma. Another common example is when someone's asthma evolves and makes them sensitive to substances that did not affect them before.

4.3.1 Case-based reasoning for asthma management

The stage when people with asthma do not know their triggers properly (uncertainty stage) is very dangerous because it is known that any person with asthma can experience a life-threatening exacerbation even if their asthma severity level is mild (the lowest) [1]. From this point of view, being able to assist and alert people with asthma during the uncertainty stage is very valuable as it can be a life-saving feature. Asthma UK states that two out of the three daily deaths from asthma in the UK in 2015 could have been prevented [11]. This can be considered as a fact supporting the need of providing people with asthma with assistance, especially during this stage.

Case-based reasoning can be used with context-awareness to provide support in the uncertainty stage by creating cases representing the knowledge of previous situations they have been exposed to. This research work studies this interaction based on the idea that using both concepts together can create synergies to solve problems dealing with evolving context adaptation [56], and adapting health procedures and strategies to personal constraints defined by contextual information [73].

The expected advantages of using case-based reasoning in the uncertainty stage can be summarised in three points. The first is that there is not enough monitoring data about situations that people with asthma have been exposed to. The second is that, even if there was a high amount of data available, it would not be possible to use it with certainty because of the high heterogeneity of asthma. This means that the data that is useful for a specific person with asthma is likely to be useless for another one because they are likely to be different. These two points refer to the available data about people with asthma in the uncertainty stage. The third advantage refers to the fact that the use of case-based reasoning can also aid in generating data for a specific person that, at some point, can be processed with machine learning techniques that do not need a high amount of data, such as decision tree algorithms.

The fact that case-based reasoning is able to create a personalised database of cases representing the knowledge about the asthma health status of a specific person makes it more suitable to provide support in the uncertainty stage. It is important to clarify some concepts that are needed to understand how case-based reasoning can provide support in the uncertainty stage. The following part of this section aims to explain these concepts and the case-based reasoning cycle for personalised asthma management that can be used to provide support in the uncertainty stage.

The indicators framing the context of a person with asthma are different to their triggers and symptoms. Their context is made of the indicators that are possible to be monitored. An indicator together with a value represent a fact, something that happens in the real world. These indicators can be connected to the triggers and symptoms of a person with asthma, however, their values represent facts that need to be interpreted. T is a set (4.1) representing all the possible triggers that a person with asthma may have (e.g. low temperature, high stress level), while S is a set (4.2) representing all the possible symptoms (e.g. breathing faster, wheezing).

$$T = \{t_1, t_2, ...t_t\} \tag{4.1}$$

$$S = \{s_1, s_2, ...s_s\} \tag{4.2}$$

Some triggers and symptoms have one or more indicators that can be linked to them in the monitoring process. For instance, the trigger *low temperatures* can be associated with indicators like minimum and maximum temperature of the day, and feels like temperature. Nevertheless, there are some triggers and symptoms that do not have indicators to be linked to them. For instance, the symptom *throat feel scratchy* has no easy-to-monitor indicators that can be linked to it in the monitoring process. Set TI (4.3) mathematically describes the relationship between the triggers that are possible to monitor and the indicators that can be used to monitor them, where a, b and c are the number of indicators that can be used to monitor triggers t_1, t_2, and t_p, respectively. Set 4.4 represents the relationship between the symptoms that are possible to monitor and the indicators that can be used to monitor them. Its interpretation is similar to the one used to explain set 4.3. The indicators that are used to monitor the symptoms are likely to be different from those used to monitor the triggers. Variables d, e and f are the number of indicators that can be used to monitor symptoms s_1, s_2 and s_n, respectively.

$$\begin{aligned} TI = \{&((t_1, i_{11}), (t_1, i_{12}), ...(t_1, i_{1a})), \\ &((t_2, i_{21}), (t_2, i_{22}), ...(t_2, i_{2b})), \\ &... \\ &((t_p, i_{p1}), (t_p, i_{p2}), ...(t_p, i_{pc}))\} \end{aligned} \tag{4.3}$$

$$SI = \{((s_1, j_{11}), (s_1, j_{12}), ...((s_1, j_{1d})),$$
$$((s_2, j_{21}), (s_2, j_{22}), ...(s_2, j_{2e})),$$
$$...$$
$$((s_n, j_{n1}), (s_n, j_{s2}), ...(s_n, j_{nf}))\} \quad (4.4)$$

A case for a CBR supporting asthma management (C_x) is made of a set of indicator-value pairs representing the triggers-related context of a person with asthma (I_x), their predicted asthma health status (hsp_x) associated with I_x, and their real asthma health status (hsr_x) associated with I_x. The monitoring indicators can be about the person (like stress or exercise level) or environmental (like temperature, humidity or pollen level). (4.5) and (4.6) mathematically describe a case that will be used for asthma management. The value of m in set 4.6 is the number of triggers-related indicators the system can monitor. Hence, I_x is made of indicators that are obtained from TI (set 4.3).

$$C_x = \{I_x, hsp_x, hsr_x\} \quad (4.5)$$

$$I_x = \{(i_1, v_{1x}), (i_2, v_{2x}), ...(i_m, v_{mx})\} \quad (4.6)$$

Figure 4.3 presents the CBR cycle for personalised asthma management. It has been created based on the CBR cycle proposed in Ref. [2]. The *new problem* is a case (C_x) without its predicted health status (hsp_x) nor its real health status (hsr_x). The CBR *retrieves* (from the database of *previous cases*) the case (C_s) that is most similar to C_x. Once C_s is selected, the CBR *reuses* its real solution (hsr_s) in order to predict the health status associated with C_x (hsp_x). The predicted solution is the predicted health status (hsp_x) of the person with asthma for the context to which s/he is exposed (I_x). Hence, $\underline{hsp_x}$ will get the value of the real health status associated with C_s (hsr_s). After this, the user determines their real health status ($\underline{hsr_x}$) in the *revision* stage, and C_x is completely defined. Finally, C_x is *retained* by storing it in the database of previous cases.

I_x (4.6) represents the exposure the person with asthma experiences. It is made of indicators from TI, which is the set represented in (4.3), and the values for these indicators. I_x includes the indicators that can be monitored by the system being build. The indicators belonging to SI (4.4) are not used to create I_x, however, if it was possible to monitor them easily enough to create a usable solution, these symptoms-related indicators could be used in the revision stage as an alternative or complementary way of confirming the

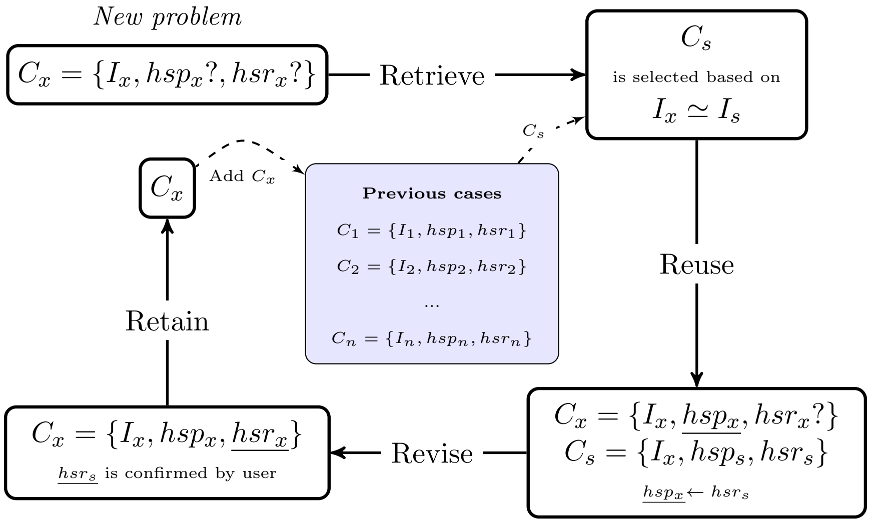

Figure 4.3: CBR cycle for personalised asthma management

real health status (hsr_x) of the person with asthma.

Some challenges arise from the proposal of using the CBR cycle for personalised asthma management. First, defining the frequency of bringing a *new case/problem* to be assessed by the CBR cycle is relevant as it must consider technical and cognitive issues. For instance, if the CBR is implemented in a mobile application, concerns about processing/storage capacity, battery duration, and not overloading users with non-relevant tasks and information should be addressed. Another issue is about what to do if there is not enough data to complete the new case to assess. This might happen because it is expected to gather data from different sources, what is always challenging [16, 84]. Some possible solutions are (i) not assessing the incomplete case, (ii) assessing the incomplete case as any other case, informing the user it is not complete. Choosing the algorithm to *retrieve* the most similar case should also be studied as it directly influences in the accuracy of the CBR component.

The interaction between the components implementing the context-aware and case-based reasoning strategies is also important to consider in the use of the CBR cycle for personalised asthma management. The way of fitting the context-aware component in the CBR cycle should be defined. Section 4.3.4 explains this issue and provides a solution to address it. This interaction is important for the process of determining the real health status (hsr_x) for a specific I_x, which is crucial to complete the *revision* stage. This is an issue as there are no commercial sensors able to monitor the asthma health status of a person constantly. Thus, an approach asking the user to input information about their health status is needed to determine hsr_x. This step is important because the hsr_x sets the ground truth to attempt the assessment of future cases, and confirm the accuracy of the predictions. This research project explores the use of the ACAC and virtual assistant technology to define the real health status of a person with asthma, and complete the case to be stored and that will be used in future predictions. The ACAC and the virtual assistant are presented in sections 4.3.3 and 4.4, respectively.

4.3.2 Synthetic evaluation of the case-based reasoning algorithm

The synthetic evaluation of the case-based reasoning cycle was done using two control cases that were defined based on the *Interviews* that were held: *Person D*, whose trigger is low temperature, and *Person E*, whose triggers are low temperature and pollen. Hourly data about weather and air pollution at Postcode NW10 0TH (London, UK) was gathered using the World Weather Online API[1] and the London Air Quality Network API[2]. The time frame of the data is from 01/01/2018 00:00:00 to 31/10/2018 23:00:00.

A case to be analysed by the case-based reasoning cycle (C_x) partially represents the weather and air pollution scenarios for a specific day (*day x*). Hence, I_x is made of the minimum temperature ($minT$), the maximum temperature ($maxT$), the average feels like temperature (FL), the average temperature (T), the average humidity level (H), the average wind gust (WG) and the average values for ozone level (O_3), particulate matter 2.5 ($PM2.5$) and particulate matter 10 ($PM10$) for *day x*.

The real health status for *day x* (hsr_x) can be 0 ("Normal health status") or 1 ("Deteriorated health status"). The real health status for *day x* for *Person D* is defined using equation 4.7. The real health status for *day x* for *Person E* is defined using equation 4.8. The limit for $maxT$ is based on the recommendations provided by Asthma UK [12], and the limit for PM10 is taken from the guideline provided by the Committee on the Medical Effects of Air Pollutants (COMEAP) [33]. The case represented by *Person E* considers PM10 to define hsr_x as it is the indicator mostly used to monitor pollen level.

$$f(maxT) = \begin{cases} 0 & \text{for } maxT \geq 10 \\ 1 & \text{else} \end{cases} \tag{4.7}$$

[1]https://www.worldweatheronline.com/developer/api/
[2]https://www.londonair.org.uk/Londonair/API/

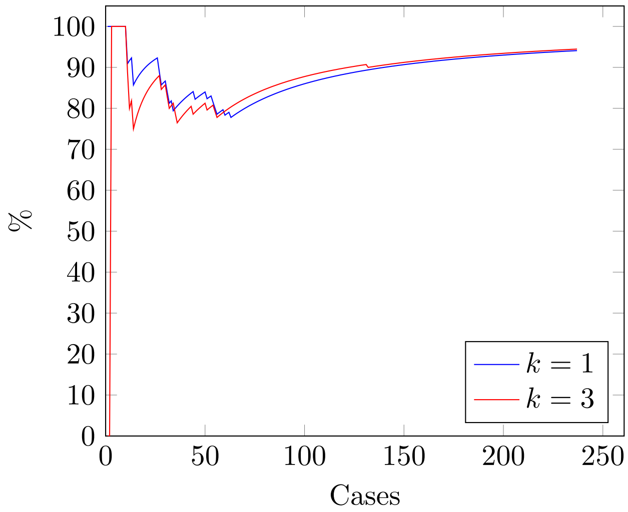

Figure 4.4: CBR cumulative accuracy for Person D (synthetic evaluation)

$$f(maxT, pm10) = \begin{cases} 0 & \text{for } maxT \geq 10 \wedge pm10 \leq 51 \\ 1 & \text{else} \end{cases} \tag{4.8}$$

The kNN algorithm was chosen for the similarity assessment in the *retrieval* stage of the case-based reasoning cycle. Its simplicity and popularity [79] aid the purpose of illustrating the application of the proposal. 66 cases were discarded because of lack of data about the days they represent. Thus, 238 cases were used for each control case and evaluated using the KNN algorithm for $k = 1$ and $k = 3$. The results of the experiment are summarised in figures 4.4 and 4.5, and table 4.2, where the cumulative accuracy (%) of the case-based reasoning cycle is shown.

The final cumulative accuracies for Person D were 94.09% ($k = 1$) and 94.47% ($k = 3$). The behaviour of the accuracies for using both values of k is also similar (Fig. 4.4). The main difference between using these two values of k is that using a $k = 1$ was noticeable more accurate than using a $k = 3$ for approximately the first 50 cases. It can be said that the difference for Person D concerning the cumulative accuracies for both values of k are not substantially different.

The final cumulative accuracies for Person E were 90.30% ($k = 1$) and 91.49% ($k = 3$). The difference between using both values of k for this control case is higher than the difference obtained for Person D. The behaviour of the accuracy trends are more similar for this case than for Person D. Further, there is never a gap between both trend lines that is as large as the largest

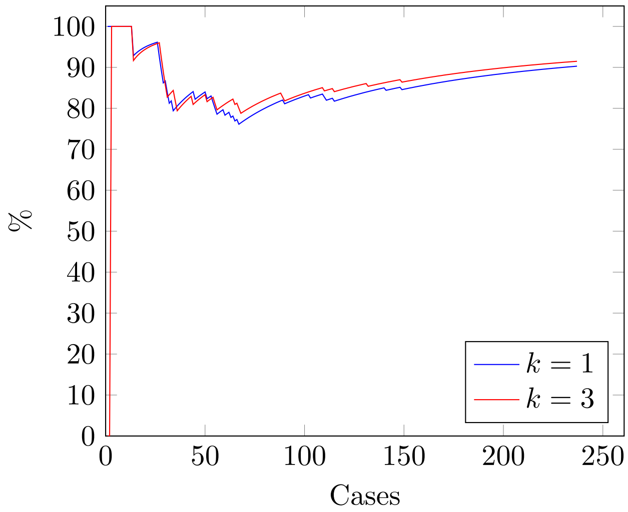

Figure 4.5: CBR cumulative accuracy for Person E (synthetic evaluation)

gap obtained for any case for Person D.

Table 4.2 shows the number of normal and deteriorated health status cases that were correctly classified in the synthetic evaluation. The column *#Cases* refers to the number of cases (days) that were classified as normal or deterioration by equations 4.7 and 4.8. The column *Correct* shows how many of these cases were correctly classified as normal or deterioration by the case-based reasoning algorithm. These results are shown for the two values of k that were used in the evaluation.

Table 4.2: CBR synthetic evaluation results summary

Participant	k	Normal health status			Deteriorated health status		
		# Cases	Correct	%	# Cases	Correct	%
Person D	k=1	205	194	94.63	32	29	90.63
	k=3	205	193	94.15	30	29	96.67
Person E	k=1	192	177	92.19	45	37	82.22
	k=3	192	179	93.23	43	36	83.72

The number of cases shown in table 4.2 evidences that the data is not balanced. Thus, the accuracy of the experiment for each k is the mean between the percentages (%) shown for each row. The values of accuracy that were obtained for Person D are 92.63% ($k = 1$) and 95.41 ($k = 3$). The values of accuracy for Person E are 87.20% ($k = 1$) and 88.48% ($k = 3$). It is also important to highlight that the number of cases that are shown in the table for both values of k are different. This is because using a $k = 3$ requires to wait until three cases are available in order to do the first classification. When a $k = 1$ is used, it only requires one previous case.

The synthetic evaluation was thought as a middle step between the theoretical proposal of using case-based reasoning for asthma management and the experiment in which the proposal is evaluated in a real-life scenario. The results of the synthetic evaluation provided strong evidence supporting idea of using case-based reasoning to aid context-aware solutions for asthma management in the uncertainty stage of the condition. The results encouraged to proceed with the evaluation of the proposal in an experiment involving people with asthma in a real-life scenario, which is reported in the next section.

4.3.3 Application example: a real case study

This section reports on the experiment that was done to evaluate the use of context-awareness together with case-based reasoning to attempt predicting the asthma health status of a person, in a real-life setting. Three people with asthma that were described in section 4.2.1 took part in this experiment. They were asked to use a mobile application that monitored some indicators about the environment they were exposed to. They also had to used the ACAC (part of the mobile application) in order to monitor their asthma health status. By doing this, the mobile application collected the environmental data required to create I_x (equation 4.5) of the cases to be assessed in the CBR cycle (Fig. 4.3), and the real health status associated with the I_x (hsr_x, equation 4.5) in order to assess the accuracy of the predictions. It has to be clarified that the system did not deliver alerts when it detected a hazardous situation. This was decided to protect the participants from the risk of delivering false positives that would increase their stress level and would provoke/worsen an asthma attack.

The Asthma Control Assessment Component (ACAC)

One of the issues of using case-based reasoning for asthma management is defining the real health status of a person when is exposed to a specific context. It is specially challenging as there are no commercial devices that can monitor the asthma health status of a person constantly. The real health status is needed to complete the case to store (*retain stage*), and to be used to predict the outcomes of future cases (*reuse stage*). Hence, if the *revision* is not completed, the accuracy of the prediction cannot be determined, and it will not be possible to use the knowledge of that case for future predictions.

One of the ways that this research project proposes to address the issue of determining the asthma health status of a person is the Asthma Control Assessment Component (ACAC), which is based on the diary version of the ACQ [52, 53, 55, 54]. The ACQ is made of questions that are answered using a scale of 7 (from 0 to 6). The average of the responses is used to assess if the asthma of the person is ‘well-controlled" or ‘not well-controlled" [53]. Four versions of the ACQ have been proposed and evaluated, concluding that the measurement properties of all four versions are almost identical [55]. The system implements the four versions: (1) assessing symptoms, Peak Expiratory Flow (PEF) and rescue bronchodilator usage, (2) assessing symptoms and rescue bronchodilator usage, (3) assessing symptoms and PEF, and (4) assessing only symptoms. The ACQ encourages to use the Forced Expiratory Volume in one second (FEV_1), however, it is suggested to use the PEF for the diary version as it is more accessible for people [53].

The ACAC allows people to assess their asthma health status by accessing to the screen that is shown in Fig. 4.6. Here, the user enters the value for their PEF test, the number of rescue bronchodilator puffs they have used in the past 24 hours, and the answer for the other questions of the ACQ. The PEF and number of rescue bronchodilator puffs values can be left in blank because not all users have access to the PEF meter at all times, and they might not remember the number of rescue puffs they have had. This flexibility lets users to choose implicitly among the four versions of the ACQ that were explained above. They can also review the history of their control tests, and edit them in case they made a mistake answering the questions. The ACAC uses the answers to calculate and show whether their asthma is well controlled or not.

The ACAC was developed for it to be implemented as part of the mobile application that is used to evaluate the use of case-based reasoning together with context-awareness for personalised asthma management. Nevertheless, before this implementation, it was considered convenient to do another experiment in which the ACAC was assessed from a usability perspective in order to make it easier to be used by the participants. The usability evaluation of the ACAC was based on the Health IT Usability Evaluation Model (Health-ITUEM), which assesses nine usability-related concepts in order to evaluate the usability aspect of health information technology. The Health-ITUEM has been validated as a tool to evaluate mHealth technology [27].

The evaluation of the ACAC included four people with asthma and five people that take or took care of people with asthma, who were asked to use

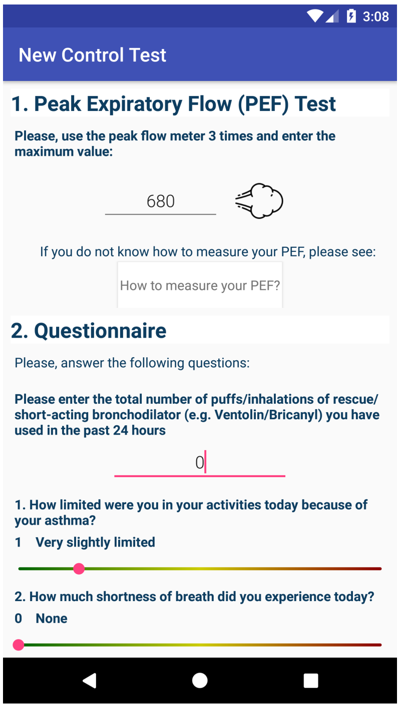

Figure 4.6: ACAC: new control test

the ACAC. They were then asked to answer a questionnaire made of nine closed and two open questions. The open questions asked about the frequency the system should ask users to complete their asthma control assessment, and about the improvements the respondents would do to the system. Two closed questions assessed the overall GUI design and user-friendliness of the ACAC. Six closed questions were meant to assessed six Health-ITUEM concepts. One of the closed questions asked about how useful the respondents perceive the idea of using previous risky situations to predict future risky scenarios. This last question was meant to know how useful this idea, which is directly linked to the use of case-based reasoning for asthma management, was perceived by the respondents. The questionnaire can be found in Appendix C or Ref. [92].

The scenario mapping the Health-ITUEM concepts for the evaluation of the Asthma Control Assessment Component (see table 4.3) was used to write the six closed questions that are associated with the Health-ITUEM. The questionnaire did not include two Health-ITUEM concepts because the Asthma Control Assessment Component of the system was considered simple enough to avoid assessing its Flexibility and Error prevention. A Likert scale going from very low (0) to very high (4) was used for the closed questions. Fig. 4.7 shows the average of the responses for the closed questions.

Table 4.3: Scenario mapping the Health-ITUEM concepts for the evaluation

Concept	Description
Information needs	The system provides enough information to complete the Asthma Control Assessment.
Completeness	The system provides enough information to know that the Asthma Control Assessment was completed.
Learnability	It is easy to learn how to perform the Asthma Control Assessment through the system.
Memorability	It is easy to remember how to perform the Asthma Control Assessment through the system.
Performance speed	It is fast to perform the Asthma Control Assessment through the system.
Competency	Users feels confident when they perform the Asthma Control Assessment through the system.

Figure 4.7 shows that the average of the responses for the quantitative questions are between 3 and 4, which are the two highest possible responses in the Likert scale that was used. All respondents assessed the idea of using previous risky situations for predicting future risky ones with 4 points, which is the highest possible response. This supports the idea of using case-based reasoning for personalised asthma management. The number of positive, neutral and negative responses for the closed questions is another interesting outcome. A negative response has a value of 0 (very bad) or 1 (bad), a neutral one has a value of 2, and a positive one has a value of 3 (good) or 4 (very good). Memorability and Performance got only positive responses. Information needs, User-friendliness and Learnability got 8 positive and 1 negative responses. Competency got 8 positive and 1 neutral responses. Design of the screen and Completeness got 7 positive and 2 neutral responses.

The improvements that were proposed by the respondents are mostly related to enhancing the GUI design of the ACAC. It was suggested to make the GUI more intuitive, and instructive about how to do the PEF test (1). It was also suggested to provide instructions about what to do if the outcome of the test is “not-well-controlled”. Two of them recommended using colours to differentiate the outcomes of the previous control tests (historical information). Two respondent suggested to use virtual assistant as a complementing way of assessing their asthma health status. One suggestion was about providing an alternative version with simpler instructions for children. Another one recom-

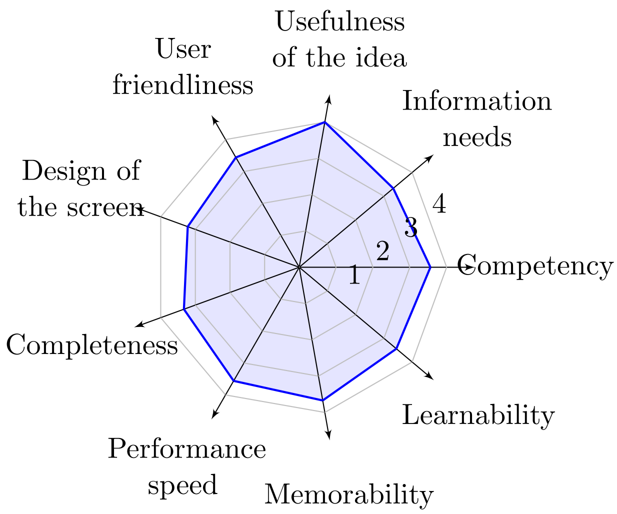

Figure 4.7: ACAC evaluation: average of the responses for the closed questions

mended to integrate the system with activity monitoring devices (e.g. smart watches) for gathering more data about the person's health status.

The responses associated with the frequency of showing the notification asking users to assess their asthma control level differs in terms of absolute values. Six of them (66.67%) explicitly suggested that the frequency of the notifications should be defined considering the characteristics of the person with asthma. The other three suggested to show the notification two times a day, three times a day, and every 10-12 hours, respectively. The difference among these responses could be related to their specific contexts but this should be further investigated. Nevertheless, there is evidence suggesting there is no unique frequency that can satisfy the requirements of all the respondents. Hence, another valuable outcome is the need for allowing users to set up the frequency of these notifications according to their specific situations.

Real-time monitoring process

The mobile application used by the participants to partially monitor their environment and asthma health status was built using Android Studio. It was adapted to being able to perform in their smartphones considering the different versions of their operating systems. The monitoring feature was built using the Snapshots feature of Google Awareness API that allows to monitor some specific indicators considering the real-time location of the smartphone [41]. This brought an important privacy issue that was addressed by collecting only the values of the indicators monitored but not the location of the user, nor any other identifiable data. Hence, no personal data was collected in the experiment.

The following indicators were collected through the mobile application in real time: outdoor temperature, outdoor temperature feels like temperature and outdoor humidity. The frequency of the collection was configured considering the participants' preferences whose main concerns were focused on their smartphones battery consumption and processing overload. They chose the mobile application to attempt the collection of the environmental data every one minute (Person A and Person C), and every two minutes (Person B). They were asked to use the ACAC at least once a day in order to monitor their asthma health status. The answers to the ACAC referred to how they felt that specific day. Hence, it was possible to create one case for each day and link it to the asthma health status of the person for that specific day. If the participant forgot to use the ACAC, then the case created for that specific day was discarded as it was not possible to know the accuracy of the prediction.

A case representing the conditions of a specific day is then made of the max. and min. temperature, max. and min. feels like temperature, and max. and min. humidity the person with asthma was exposed in that specific day. The case also include the max. and min. Particulate Matter 10 (PM10) values at a specific place in that specific day. It was not possible to collect the PM10 values using the location capability of the smartphones as there is no service providing these values at all the locations the participants performed their activities. A place that was near to the participants work place and in which PM10 was able to be monitored was chosen. The London Air Quality Network [58] was used to monitor the PM10 values at Enfield, London.

The monitoring of the indicators would be improved in order to create cases that represent more accurately the environmental conditions participants were exposed to. For instance, it would be better to having been able to monitor the indoor conditions of the places the participants frequented, however, this was not possible given the fact that there were no enough resources to install the required equipment at those places. Another example is having been able to monitor the PM10 values the participants were exposed to in real time, like how it was done for the weather conditions. Nevertheless, the fact that none of them were allergic to the substances that are monitored through PM10 levels is expected not to influence in the results of the experiment.

Results

The algorithm that was chosen to assess the similarity between cases in the retrieval stage of the CBR cycle for asthma management was the Nearest Neighbour (NN). The reason for this choice is based on the fact that this case study focuses on presenting a practical example of how context-awareness can be used together with case-based reasoning to determining the asthma health status of a person given some specifics environmental conditions. This case study does not aim at exploring most effective way to retrieve the most similar case to the one that is being assessed in the case-based reasoning cycle. Nevertheless, knowing the most appropriate algorithm to be used in the *retrieval* stage is relevant as it directly affects the accuracy of the proposal and it should be further studied. Chapter 6 discusses more the importance of doing research in finding the algorithms that fit better when using the CBR cycle for asthma management.

Person A was able to assess their asthma health status during 51 days, however, they did not assess their health status as deteriorated in any of those days. Thus, given the fact that there were no cases representing a deteriorated health status, the accuracy score for this case was 100%. An important outcome of this case is that using context-awareness and case-based reasoning in this situation does not deliver false positive. This is because a person not suffering episodes of deterioration does not generate cases for deteriorated asthma health status and, thus, it is not possible for the CBR cycle to reuse a previous case whose real outcome was deterioration.

Person B assessed their asthma status for 40 days but it was only possible to create 32 cases because there was not enough weather and environmental data to create cases for 8 days. The case for the first day is not considered in the assessment of the accuracy as the CBR cycle cannot predict if there are not previous cases to use. The final overall accuracy for Person B was 74.19%. The evolution of this accuracy is shown in Fig. 4.8. The trend shows the accuracy never went over 78%.

The asthma of Person C is triggered by demanding exercises. Because of this, the mobile application had to be adapted for Person C. The amount of demanding exercise that a person does is difficult to measure because it can be considered as a higher-level context that is the result assessing several indicators (like oxygen level, heart rate, among others). For this experiment, it was decided to add one simple question asking Person C to rate from 0 to 10 how demanding the exercises they did during the day were. The scope of this

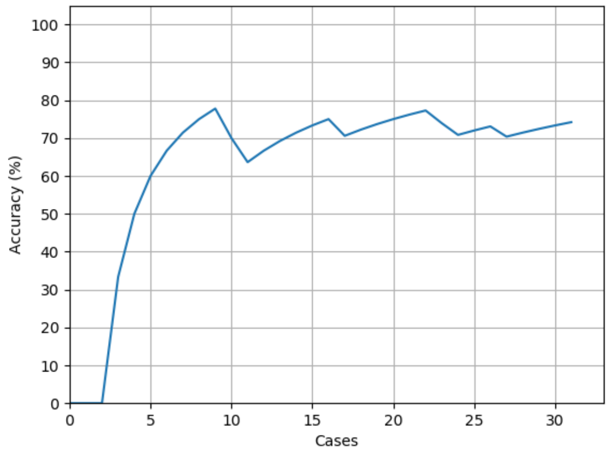

Figure 4.8: CBR evaluation: cumulative accuracy for Person B

case study does not aim at finding the best automated way of measuring the amount of demanding exercises a person does and, although there are devices that can measure this, the resources of the project constrained the acquisition of this type of devices.

Person C assessed their asthma health status for 59 days. However, 7 cases were discarded because there was not enough weather and environmental data available to complete the cases for those 7 days. The results for this participant are based on 52 cases representing 52 days. As it was done for Person B, the case representing the first day was not included in the assessment of the accuracy. Person C had a normal health status in 40 days and a deteriorated one in 12 days. The cumulative accuracy for Person C was 76.47%. Fig. 4.9 shows the accuracy trend for Person C. The cumulative accuracy never went below 66.67% and it reached high values since the first days.

Table 4.4: CBR evaluation results summary

Participant	Cumulative			Normal health status			Deteriorated health status		
	# Cases	Correct	%	# Cases	Correct	%	# Cases	Correct	%
Person A	50	50	100.00	50	50	100.00	0	0	–
Person B	31	23	74.19	13	6	46.15	18	17	94.44
Person C	51	39	76.47	40	34	85.00	11	5	45.45

Table 4.4 presents a comparison of the results of each participant. The *Cumulative* columns refer to the total number of cases that were assessed, the number of cases that were correctly classified, and the cumulative accuracy. The columns belonging to *Normal health status* show the number of cases that

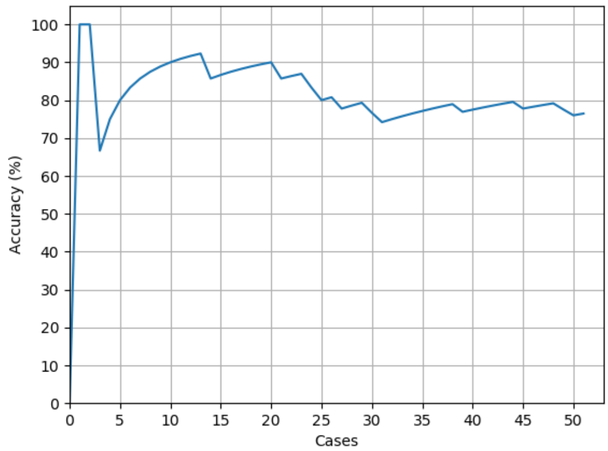

Figure 4.9: CBR evaluation: cumulative accuracy for Person C

should have been classified as *Normal*, how many of these cases were correctly classified as *Normal*, and the accuracy when these cases were classified. This explanation is also valid for the columns that refer to *Deteriorated health status*. Although the number of cases assessed for Person B is lower, it is evident that the cumulative accuracy for Person B is also lower.

Table 4.4 shows that Person C had more *"normal cases"* to be classified (40 cases, 78.4%), while Person B had more *"deterioration cases"* (18 cases, 64.5%). The accuracy to classify *"normal cases"* for Person C (85%) is considerably higher than for Person B (46.15%). However, the accuracy to classify *"deterioration cases"* for Person C (45.45%) is significantly lower than for Person B (94.44%). The fact that Person B and Person C had less *"normal cases"* and *"deterioration cases"*, respectively, might have had an impact on these results. As it was explained before, the results for Person A are different because they never experienced a deteriorated health status.

Table 4.4 evidences that the data obtained for this experiment is imbalanced. The accuracy is then the mean between the accuracies obtained for the *normal cases* and the *deteriorated cases*. Hence, the accuracy for Person B was 70.3%, and the accuracy for Person C was 65.23%. Although these results may not seem to be very impressive at first, it is important to clarify that the participants were not asked to stop their treatments as an ethical decision of not putting them in danger.

Considering that this part of the proposal is meant to be used by people still not knowing their triggers properly, which means that they still do not know their treatments properly, it is expected to have better accuracies when people do not have an already customised treatment. Person C, whose trigger is sudden temperature changes, is a clear example of this. The temperature differences would have been enough to trigger a deterioration in Person C's health status. Nevertheless, this person took preventive measures (like wearing appropriate clothes) to avoid being exposed to sudden temperature changes. Thus, no deteriorated cases were generated for this person.

The results of the experiment for Person B were also influenced by their treatment. Person B is sensitive to low temperatures and humidity, and the city where this experiment was done (London, UK) is both cold and humid enough for Person B to be affected. Person B was aware of this and used appropriate clothes to avoid being exposed to low temperatures. Nevertheless, although there are devices that can help to control humidity levels at indoor places, this participant did not use this type of devices. Person B was also taking preventive medication (controller twice a day) for not being affected by the weather conditions. This is also expected to have influenced the results because this medication is meant to reduce the intensity of their symptoms when they have a deterioration in their health status.

4.3.4 Context-aware reasoning and case-based reasoning interaction

The interaction between the system components implementing the context-aware reasoning and case-based reasoning strategies should be carefully considered to ensure an appropriate performance of a solution built based on ADAPT to support personalised asthma management. Figure 4.3 shows the stages the CBR component performs (CBR cycle for personalised asthma management). The context-aware reasoning component plays a key role in (a) bringing the *new case* that will be assessed, (b) the *revision stage* that confirms the person's real asthma health status, and (c) delivering the notifications to the right recipients. A summary of this interaction is shown in algorithm 1, which is explain below.

The C-AR component acquires the context-related data that is then delivered to the CBR component that uses it to create the *new case*. This procedure triggers the CBR cycle shown in Fig. 4.3. The role played by the C-AR component at this stage is crucial as it is the one bringing all data to be processed and, because of this, significant issues should be considered. From an Internet of Things (IoT) perspective, it is important to select the right

Algorithm 1 Interaction between the context-awareness (C-AR) and case-based reasoning (CBR) components

C-AR collects contextual data and delivers it to CBR.
CBR creates the *new case* (C_x) based on the data delivered by the C-AR.
CBR *retrieves* the most similar case to C_x (C_s).
CBR *reuses* the solution of C_s (hsr_s) to predict the solution of C_x (hsp_x).
CBR sends the prediction (hsp_x) to the C-AR.
C-AR shows the prediction to the user.
C-AR confirms user's real health status (hsr_x) through the ACAC or VA.
if hsr_x is *Deterioration* **then**
    C-AR triggers the personalised notification protocol.
end if
C-AR sends hsr_x to CBR.
CBR uses hsr_x to *revise* and complete C_x.
CBR *retains* C_x.

sensors or virtual sensors (APIs) to collect reliable data. Moreover, using the proper techniques to acquire and model the data in order to create the *new case* is also critical [84]. From a software development point of view, collecting the context-related data from several heterogeneous sources and translating it into a more understandable format (*new case*) should also be considered as an essential challenge to address [7].

The *revision* is another stage in which context-awareness plays a key role. Here, after *reusing* the solution of the most similar case to the one that is being assessed, the person has to confirm whether the predicted solution is accurate or not by assessing their asthma health status. Context-awareness is used here to collect the real asthma health status. The ideal way of doing this would be through a device monitoring their asthma health status constantly. Nevertheless, there are no commercial devices capable of doing this mainly because their symptoms are as heterogeneous as their triggers. Further, monitoring just one indicator (like heart rate) is not enough because it may vary not only because of asthma-related reasons. This makes this task more complex as several indicators should be monitored and processed to determine someone's asthma health status accurately and in real time.

Two ways of determining the real asthma health status of a person to complete the *revision* stage are explored in this research project. The first one is the ACAC that was implemented in the system as the tool that people use to monitor their asthma health status. The ACAC is explained in section 4.3.3. The second one is the use of a virtual assistant that interprets the user's voice commands and detects if their asthma health status is normal or deteriorated based on their commands. The study of this virtual assistant is presented in section 4.4.

Context-aware reasoning has another relevant task to perform between the *revision* and *retain* stages, which is to deploy the notification protocol depending on the outcome of the *revision*. The user personalises this protocol by choosing what people to contact and how to contact them in case of a deterioration in their health. This is done through the *Personalisation layer* (Fig. 4.1). It can be argued that the notification protocol could be deployed between the *reuse* and *revision*, however, it is considered more convenient to do it after the real health status is confirmed, following a pull approach. The novelty of using context-awareness together with case-based reasoning to predict someone's asthma health status is the main reason of the suggestion to use a more conservative approach when it comes to deliver notifications.

Section 4.4 presents how virtual assistant technology can be used to support the use of case-based reasoning and context-awareness for personalised asthma management. More details of the interaction between the context-awareness and case-based reasoning components are provided through the explanation of the sequence diagrams shown in Fig. 4.11 and 4.12.

Balancing the use of case-based reasoning

This section presents three scenarios representing the three potential situations a person with asthma may be in. The way of using context-awareness and case-based reasoning for each scenario is explained. The three scenarios are summarised in algorithm 2.

The first two scenarios refer to extreme situations. The first is a person properly knowing their triggers (uncertainty level is none). In this case, the CBR component of ADAPT is not used, and the control limits are set up to monitor the indicators linked to their triggers. Hence, only the C-AR component of ADAPT is used and performs depending on the personalised monitoring process chose by the user. The second scenario is a person not knowing their triggers (uncertainty is the highest possible). In this case, the CBR component is used with the aim of storing the knowledge about previous experiences to attempt the prediction of their health status. The C-AR component then performs all its functions to support the CBR component. These functions are those shown in algorithm 1. Nevertheless, the real-time analysis of the indicators is only performed by the CBR component because

Algorithm 2 Balancing context-awareness (C-AR) and case-based reasoning (CBR)

input: *uncertainty* is the uncertainty level of the person with asthma as regards to their triggers
if *uncertainty* is none **then**
    User chooses the indicators to monitor
    User defines the control limits
    C-AR component monitors these indicators
else if *uncertainty* is the highest **then**
    User activates the CBR component
    C-AR component collects context-related data to create the new cases for the CBR component
else
    User chooses the indicators to monitor
    User defines the control limits
    C-AR component monitors these indicators
    User activates the CBR component
    C-AR component collects context-related data to create the new cases for the CBR component
end if

the user do not have enough knowledge to personalise the monitoring process the C-AR component should perform.

The third scenario is a hybrid situation in which the person partially knows their triggers but there are some that have not been discovered yet. For instance, they might know that low temperatures is their trigger but they still have exacerbations even without being exposed to low temperatures. Thus, they would like to activate the CBR component as a complementary option. In this situation, the C-AR component analyses those indicators having monitoring control limits already configured by the user, and the CBR one still performs the CBR cycle to detect potentially hazardous situations.

The second and third scenarios could be supported by using asthma management guidelines that provide some control limit suggestions for the indicators. These guidelines can also be used to help the CBR component when there is no enough representative cases to attempt predictions, or when its accuracy is low or unstable.

4.4 Virtual assistant supporting context-awareness and case-based reasoning for personalised asthma management

This section explains the development and validation of a virtual assistant that facilitates the application of context-aware reasoning and case-based reasoning for personalised asthma management that was explained in section 4.3. The architecture and sequence diagrams of the system implementing these technologies are explained in section 4.4.1 in order to show a more technical perspective of how a system built based on ADAPT performs. Sections 4.4.2 provides details about the experiment that was done with the aim of validating the text classifier. Following the user-centric approach (U-CIEDP), this experiment involved real people with asthma and carers.

4.4.1 System design: architecture and sequence diagrams

The architecture diagram highlighting the interaction among the virtual assistant, the context-aware reasoning and the case-based reasoning components is shown in Fig. 4.10. It is important to clarify that this diagram does not represent the whole system explained in Fig. 4.1 as it does not include the *Personalisation* and *Reporting* layers. The diagram shows how the virtual assistant can be used for a specific purpose, which is confirming and completing a case with the real health status of the person with asthma in the *revision stage* of the CBR cycle for asthma management (see Fig. 4.3). A virtual assistant supporting personalised asthma management can also be used to enhance the performance of the system in other situations (e.g. asking for a specific report considering the personalisation previously done by the user).

The virtual assistant is represented by the *Speech-to-Text*, *Text-to-Speech* and *Text Classifier* elements. The first one transforms a voice command said by the user into text. The second one does the opposite. It gets a phrase (text) and transforms it into a voice command that is then delivered to the user. The responsibility of the *Text Classifier* is to interpret the phrase (text) the user said into *normal* or *deterioration* state. In this case, the virtual assistant enhances the the human-computer interaction of the proposal by providing the user with a complement to the ACAC. This section describes the performance of the system when the user chooses to enter their real health status through the virtual assistant and not through the ACAC.

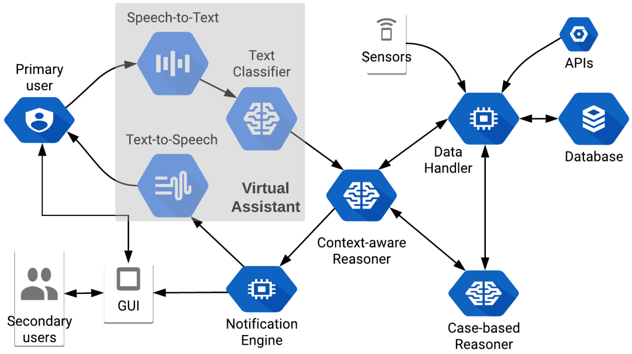

Figure 4.10: Architecture diagram of the system

The sequence diagram of the system for when it is used under a pull approach is shown in Fig. 4.11. This pull approach is performed when the user decides to use the virtual assistant to provide the system with their real health status. The user does this to keep record of their asthma health status and increase the knowledge of the system (i.e. increase the number of cases) as regards to their condition. For this, the user sends a voice command (1) through the *Speech-to-Text (S2T)* that transforms it into a phrase as a text (2). This text is then sent to the *Text Classifier* (3) that interprets if the phrase reflects a normal or deteriorated status (4).

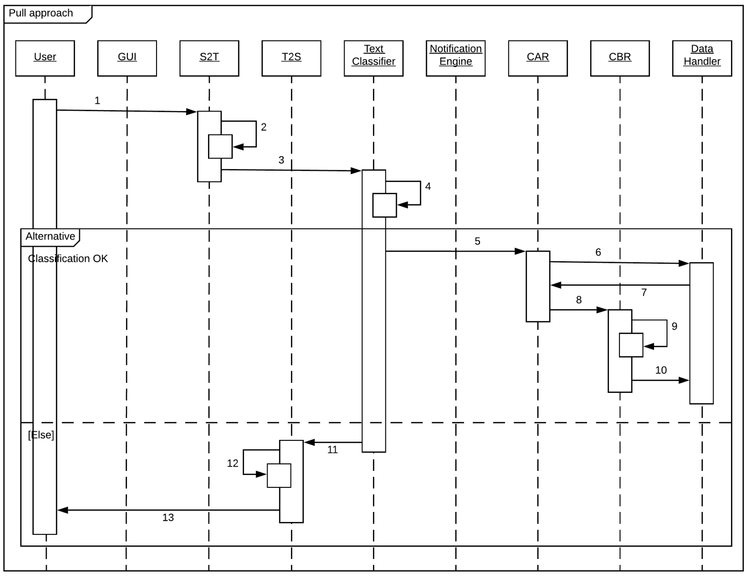

Figure 4.11: Sequence diagram: pull approach

The accuracy threshold of the outcome given by the *Text Classifier* is important as it is used to define whether the classification is *good enough* or not. If it is good enough, the system then performs the steps needed to store the new case. Thus, the outcome of the classification is sent (5) to the *CAR component* that, through the *Data Handler*, stores it in the database (6) and gets the required context-related data to create a new case (7). These data are then sent (8) to the *CBR component* that creates a new case and assesses it (9), following the CBR cycle explained in Fig. 4.3. The *retain* stage of the cycle is done through the *Data Handler* that stores the new case in the database of cases (10). If the outcome of the *Text Classifier* is not *good enough*, the system activates (11) the *Text-to-Speech (T2S)* for it to create a voice command (12) that is delivered to the user (13) asking them to say a new phrase reflecting their health status.

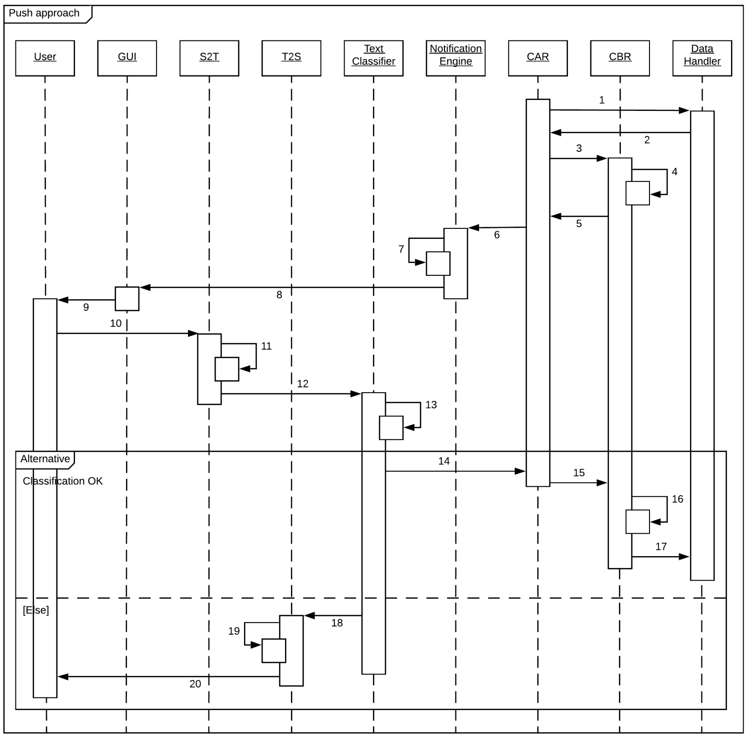

Figure 4.12: Sequence diagram: push approach

Figure 4.12 shows the behaviour of the system when it is used under a push approach in which the system triggers the analysis of the situation the user is exposed to. The *CAR* begins the process by getting the context-related data that is needed to create a new case (1,2). These data are then sent (3) to the

CBR that creates the new case and predicts the health status for that case (4). This prediction is sent to the *CAR* (5) who delivers it to the *Notification Engine (NE)* (6). The *NE* creates a notification (7) and sends it to the user through the *GUI* (8,9). The notification asks the user to say how they feel, and it is shown on the mobile phone of the user who activates the virtual assistant by tapping on it. When this happens, the user says a voice command that is received by the *S2T* (10) who transforms it into a text (11) that is sent to the *Text Classifier* (12). The *Text Classifier* classifies the phrase into normal or deterioration health status (13), and sends this outcome to the *CBR* through the *CAR* (14, 15). The *CBR* uses this outcome to complete the *revision* stage of the CBR cycle (16), and stores the case in the database of cases through the *Data Handler*. The alternative scenario shown in Fig. 4.12 is the same as the one explained above for Fig. 4.11 in which it is explained what the system does in case the outcome of the *Text Classifier* does not reach the accuracy threshold.

The behaviour of the system that is shown in Fig. 4.11 and Fig. 4.12 refers to using the proposal in the *uncertainty stage* when the user does not know their triggers properly. As it can be noticed, the analysis performed by the *CAR* in order to detect a hazardous situation based on previously personalised monitoring preferences is not shown. Even though, it is evident that the *CAR* is the main component allowing the application of the proposal. The *CAR* is in charge of transforming the collected context-related data (from the *Data Handler* or *Virtual Assistant*) into meaningful data that the *CBR* is able to process. Once the *CBR* generates a prediction, the *CAR* is also in charge of notifying the user about the prediction and asking them to confirm their asthma health status in order to complete the CBR cycle for personalised asthma management. The *CAR* can be seen as the *bottleneck* of the process and, thus, it has to be carefully developed to enhance the performance of a system implementing the proposal.

4.4.2 Training and validation of the text classifier

This section reports on the experiment that was done in order to train and validate the *Text Classifier* that interprets a phrase said by the user into *normal* or *deteriorated* health status.

The *Text Classifier* was trained with a set of phrases that were generated using the most common symptoms experienced by people with asthma. Following our user-centric approach, these symptoms were chosen based on the outcomes of the *Personalisation questionnaire* in which the respondents were asked to choose the symptoms they experience when an asthma exacerbation occurs (see table 3.2). The phrases were created in order to represent the five most common symptoms chosen by the 42 respondents. Moreover, other more general phrases (like *"My asthma is bad"* or *"My health is not OK"*) were also included for allowing people with asthma to use less asthma-specific phrases to refer to their health status. The list of phrases that were used to train the *Text Classifier* can be found in Ref. [97].

The training of the *Text Classifier* was done using Python 3.7 through the free software machine learning library Scikit-learn [83]. PyCharm was the IDE chosen for this experiment. The bag of words concept was used to transform the phrases into vector features that were then assessed by the classification algorithms offered by Scikit-learn. The algorithms that showed the best results in the training process were the Random Forest (100%), Nu-Support Vector (98.36%) and Decision Tree (100%) classifiers.

The validation of the *Text Classifier* was done through an experiment involving people with asthma that were asked through a questionnaire for the phrases they would use to express that their asthma health status is *normal* or *deteriorated*. They were contacted through Asthma UK who spread the questionnaire among the members of their Patient Advisory Group, which is part of the Asthma UK Centre for Applied Research [13]. From the 107 phrases that were collected (18 respondents), 43 phrases refered to *normal* and 64 refered to *deteriorated* health status. The list of phrases that were used for the validation can be found in Ref. [98]. These phrases have been previously improved by fixing some typos. The list shows only 103 phrases because duplicates were removed.

The outcomes of the training and validation show that the three algorithms are similarly accurate. Table 4.5 shows the accuracy obtained in the training and validation processes. The accuracy that is shown for the validation has been disaggregated to show how many phrases reffering to normal and deteriorated health status were incorrectly classified. As it can be seen, the Nu-Support Vector Machine and the Decision Tree classifiers are the algorithms that incorrectly classified less phrases (17/103) in the validation, while the Random Forest incorrectly classified 18/103 phrases. Fifteen of the incorrectly classified phrases are common to the three classification algorithms. The phrases that were incorrectly classified can be found in Ref. [96].

This section reported on one of the objectives of this research work, which

Table 4.5: Text classifier: accuracy of the training and validation

Classification algorithm	Training	Validation					
		Normal health status			Deteriorated health status		
		# Phrases	Correct	%	# Phrases	Correct	%
Random Forest	100%	43	32	74.42%	60	53	88.33%
Nu-Support Vector Machine	98.36%	43	31	72.09%	60	55	91.67%
Decision Tree	100%	43	33	76.74%	60	53	88.33%

is to explore how virtual assistant technology can be used to support asthma management. The case study of this section was chosen as an example to show how a virtual assistant technology can be used as an alternative way of performing a specific task in using case-based reasoning and context awareness for personalised asthma management. Because of this, it is important to clarify that the scope of this research project does not focus on developing more efficient text classification algorithms targeted to improve the accuracy of the specific task of recognising *normal* and *deterioration* asthma health status. However, the aim of developing the virtual assistant and text classifier for this specific purpose is to explain and show an example of how virtual assistant technology can support asthma management. This example was used in the validation process of ADAPT that included stakeholders of the asthma management process. This validation is reported in chapter 5.

4.5 Chapter summary

This chapter presented ADAPT as the main contribution of the research project reported in this thesis. The approach is described putting a special emphasis on how it supports the customisation of a solution depending on the characteristics of the person with asthma. The chapter explains ADAPT context dimensions and the use of case-based reasoning for personalised asthma management, which led to the study of the interaction between context-aware reasoning and case-based reasoning in the development of intelligent environments. Virtual assistant technology is also described as a complementing technology enhancing the HCI component of a solution built based on ADAPT.

The definition of ADAPT context dimensions is the most important part of the approach because they are the basis for the development of the preventive and reactive features of solutions supporting personalised asthma management. ADAPT context dimensions allow to support decision-making in the asthma management process, considering the customisation of this process as the most relevant issue to address the heterogeneity of asthma. The case-based reasoning cycle for personalised asthma management is presented as a suitable tool to aid people in the uncertainty stage of asthma management. The synthetic and real-life evaluation of the CBR cycle for personalised asthma management show positive results. The interaction between the C-AR and CBR components of ADAPT is described. This interaction permits to deliver appropriate alerts and balance the use of both techniques in order to provide support to people not knowing their triggers properly. The C-AR component, which is based on ADAPT context dimensions, is highlighted as the main element of ADAPT that allows all the other elements of the approach to perform accordingly to the customisation made by the user.

The use of a virtual assistant as a complementing technology to determining the real health status of a person with asthma is presented as a case study. The experiment that was done to develop the text classifier of the virtual assistant is described as an example of how this technology could help to enhance the HCI component of a solution supporting personalised asthma management. This virtual assistant is linked to the C-AR and CBR components of ADAPT by showing how the three elements interact in a solution built based on the approach.

Chapter 5

Validation of ADAPT

This chapter presents the validation of ADAPT through the involvement of people affected by asthma that assessed a mobile application (prototype) built following the approach. The process followed for the validation is explained with a special emphasis on the inclusion of people affected by asthma as participants. The prototype that was used in the validation is described in section 5.1. Finally, the outcomes of the validation are presented in section 5.2.

The validation of ADAPT involved real users that assessed a mobile application whose features were implemented based on the elements of the approach. A demonstration of the prototype was given to the participants who were then asked to answer a questionnaire in which they assessed the usefulness of each feature of the prototype. Each feature was assesed using the Likert scale (very useless - useless - neutral - useful - very useful). The questionnaire also included open questions that asked the participants to explain their reasons to choose their answers about the usefulness of the features, and to provide feedback about how to improve the system features. Another question asked to rank the features from the most important to the least important. This question helped in the assessment of what elements of the proposal were perceived as more or less important by the users. The questionnaire can be found in Appendix E or Ref. [95].

The collaboration with Asthma UK helped to contact people with asthma and carers of people with asthma willing to be participants. The experiment was designed for it be done in face-to-face sessions, and through remote meeting using Skype for the video conference. Vysor[1] was the software used to share the screen of the smartphone in which the prototype was installed, for

[1] www.vysor.io

Table 5.1: Features implementing the main elements of the ADAPT

Features	C-AR dimensions					CBR	VA
	Environmental	Internal	Communication	Medication	Location		
PM	✓	✓	✓	–	✓	–	–
CO	–	–	✓	–	✓	✓	–
TA	✓	✓	✓	–	✓	✓	–
CTM	–	✓	–	–	✓	✓	–
MR	–	–	–	✓	–	–	–
VA	–	–	–	–	–	–	✓

the explanation in the remote meetings. The demonstration was designed to show the features in the same way for all the participants, regardless the type of meeting they chose. Thus, it was possible to recruit more participants for the experiment. Eight (8) participants assisted to face-to-face meetings, and two (2) did it through Skype. The experiment involved 6 people with asthma, 2 experts in respiratory conditions, 1 non-professional carer, and 1 person that has asthma and is also a non-professional carer of a person with asthma. The sessions lasted between 50 and 80 minutes.

5.1 Description of the prototype

The prototype implements six main features: personalised monitoring, communication, triggers assistance, control test management, virtual assistant, and medication reminder. The features are linked to the elements of ADAPT. Table 5.1 shows the most relevant relationships among the main elements of ADAPT (columns) and the prototype features (rows). The *location* context dimension is less explicitly shown in the system than the other ones because it is mostly implemented in the background activities the prototype executes.

The personalised monitoring feature (PM) allows to track the environmental indicators at the places of interest (location). It also monitors the internal indicators chosen by the user, and delivers alerts to people chosen by the user (communication). The communication feature (CO) permits to choose the people to involve in the asthma management process. The location dimension is linked to the CO feature because, in case of emergency, the location of the person having the emergency is sent to those chosen in the CO feature. The CBR cycle for personalised asthma management is also linked to this feature because it sends a warning in the form of a notification to the people chosen by the person when a hazard is detected and confirmed.

The triggers assistance (TA) feature is linked to the environmental, internal, communication and location context dimensions in a similar way than the PM feature is. The TA feature also implements the CBR cycle for asthma management and its interaction with the context-aware component. The control tests management (CTM) feature lets keep track of the asthma health status of a person with asthma through the ACAC. This is important to define part of the internal context dimension as it determines whether their asthma is deteriorated or not. The CTM also associates the outcome of a control test to the location where it was done, and allows the creation of control test reminders that are shown as notification (or alarms if the user chooses this option). Moreover, when the TA feature is activated, the outcomes of the control tests are linked to CBR cycle in the *revision stage* (see Fig. 4.3).

The medication reminder (MR) allows to set reminders that are shown as notifications or alarms. This feature fulfils one of the requirements gathered in the *personalisation questionnaire*. The virtual assistant (VA) feature was implemented as an application example of how virtual assistant technology can be used to complement the other features. In this research project, the VA implemented the feature explained in section 4.4. The use of virtual assistant technology is thought as a complement to the other features of the system, which means that its application can be expanded.

The triggers and symptoms context dimension has not been included in table 5.1 because it was implemented as an informative component allowing the users to choose their triggers and symptoms from a list. Although it has no relevant impact or relationship with the other features, in the future, the triggers and symptoms chosen may be used to customise guidelines about preventives measures, and automatically create an initial configuration of the indicators to track and their control limits. However, this has to be further investigated as it is not part of the scope of this research project.

Figures 5.1-5.4 show some screens of the prototype. Fig. 5.1 is the main screen of the mobile application. The options shown on the main screen are not linked to only one specific feature. The features are distributed throughout the five options. For instance, the *Control your asthma* option takes to the screen shown in Fig. 5.2, which is related to the CTM feature. Nevertheless, the CTM feature is also implemented in the *Personalise your asthma* option of the main screen that takes users to the screen shown in Fig. 5.3. Here, the *Triggers assistance* feature also allows to set up the frequency of the control tests (CTM feature) in order to create the cases for the CBR component.

The personalised monitoring (PM) feature needs to be configured before

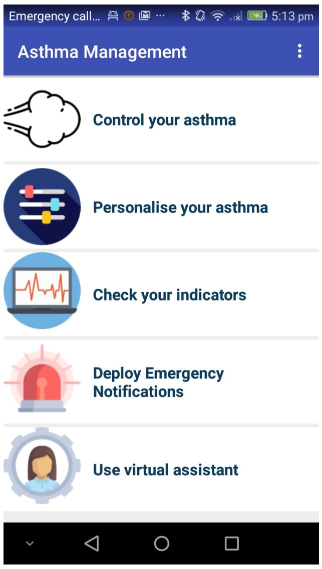

Figure 5.1: Prototype main screen

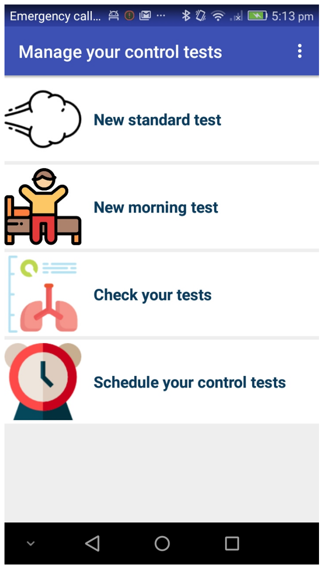

Figure 5.2: Prototype CTM screen

it can deliver personalised reports and notifications. This is done by choosing the *Monitoring* option from the screen shown in Fig 5.3. This option allows to choose the indicators they want to monitor at their places of interest. It also allows to choose the internal indicators (e.g. hear rate, weight) they want to keep track. The mobile application uses this configuration to show personalised reports, like the one shown in Fig. 5.4. This personalised report is accessed from the main screen by choosing the *Check your indicators* option. The notifications are delivered when at least one control limit has been breached and, when the user tap on the notification, the mobile application takes them to the personalised report (Fig. 5.4).

The *Personal information* and *Triggers & Symptoms* options in Fig. 5.3 allows to enter user's personal information, and choose their triggers and symptoms from a list, respectively. The *People* option allows to define the people that are going to be involved in the asthma management process of the user by assigning them at least one of the three possible privileges explained in the *communication* context dimension (see section 4.2). Once this is configured, the user can reach the people chosen to be contacted in emergency situations using the *Deploy Emergency Notifications* option from the main screen (Fig. 5.1). This option is thought to be available to use even if the smartphone screen is locked, so the user does not have to unlock the phone and open the application in case of emergency.

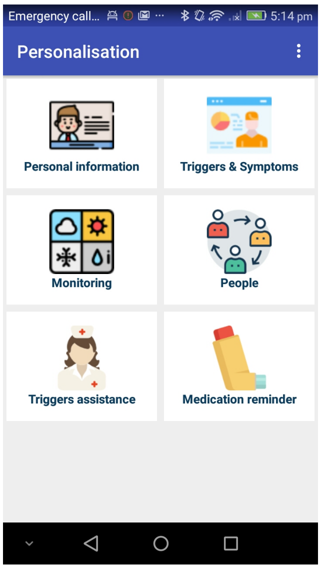

Figure 5.3: Prototype personalisation

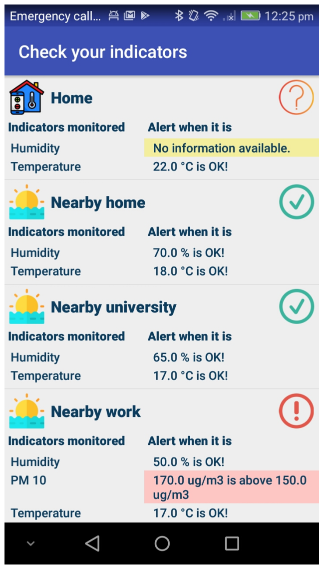

Figure 5.4: Prototype report example

The CBR cycle for asthma management is used when the *Triggers assistance* option (Fig. 5.3) is activated by the user. This option can be used by those not knowing their triggers properly (uncertainty stage). The system must be able to execute the *personalised monitoring* and *triggers assistance* options at the same time or individually. These options permit users to balance the usage of context-awareness and case-based reasoning according to algorithm 2, which is explained in section 4.3.4. The *Medication reminder* option (Fig. 5.3) allows to configure reminders to take their medication. Finally, when the *Use virtual assistant* option (Fig. 5.1) is chosen, the virtual assistant is activated to interact with the user. The virtual assistant should also be available to use with the smartphone screen locked. The ideal case would be for this VA targeted to people with asthma to be implemented as part of the native VA of the mobile device the system is installed.

5.2 Results of the validation

The assessment of the usefulness of the prototype features are summarised in Fig. 5.5, which shows the percentage of the participants that assessed the features as very useless, useless, neutral, useful and very useful. The communication, triggers assistance and control test management features were assessed as very useful by all the participants (100%). The personalised monitoring feature was assessed as very useful by 9 participants (90%) and as useful by 1 participant (10%). The medication reminder feature was assessed as very useful by 8 participants (80%) and as useful by 2 participants (20%). Finally, the virtual assistant feature was assessed as very useful by 3 participants (30%), as useful by 6 participants (60%) and as neutral by 1 participant (10%).

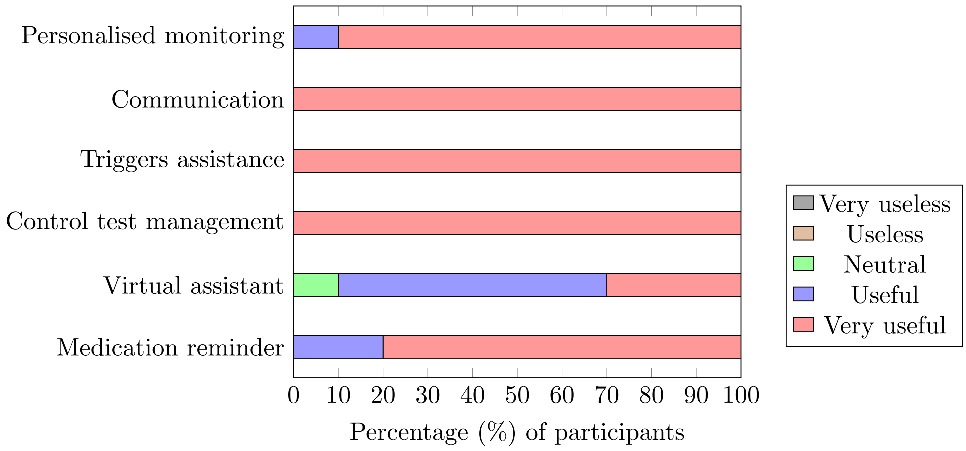

Figure 5.5: Perceived usefulness of the prototype features

Table 5.2 summarises the answers to the question asking to rank the features from the most important to the least important. The value of 1 was assigned to the feature that was considered by the participant as the most important, and the value of 6 was assigned to the one considered as the least important. Thus, the average column reflects the average of the answers given by the participants. The control test management feature was the highest-ranked (average of 2.2) and the VA feature was the lowest-ranked (5.4).

Table 5.2: Ranking of the prototype features

Rank	Feature	Average
1 (Highest)	Control test management	2.2
2	Personalised monitoring	2.5
3	Triggers assistance	3
4	Communication	3.7
5	Medication reminders	4.2
6 (Lowest)	Virtual assistant	5.4

The analysis of the answers to the open questions for each feature will be shown in the order the features appear in table 5.2. The CTM was the feature with the highest rank. The points that the participants liked the most about this feature are: allowing them to keep constant track of their condition, its easiness to use, it being based on the ACQ, and it being able to share the results with professionals. The points of improvement are: generating graphical summary reports of the outcomes, making it available to professionals and researchers, improving its design, creating a version for children, linking the results to exposure, and being able to enter/calculate their personal best.

The second highest ranked feature was the personalised monitoring. The participants valued the preventive characteristic of this feature and its ability to be configured considering their needs. They perceived this feature as it following the technological trend of monitoring devices, and fulfilling their expectations. One expert said it would have a broad impact because respiratory conditions are a challenge to address in the near future. The suggested improvements are mainly related to the design (e.g. using better colours and symbols) and creating a better guide (more interactive) for the users to know more about the available indicators to monitor.

The triggers assistance feature was perceived as a very important preventive feature for those not knowing their condition properly. Two participants even agreed that it would be useful for experienced patients that are negligent. The opportunity of providing insights about the collected data was considered as the most important part of this feature. The improvements mainly refer to providing reports summarising the data gathered through this feature, improving the explanation of how to use it, sharing the data with professionals, and suggest possible triggers from the data. One participant expressed concern for the accuracy of the feature, considering that some people's asthma might be triggered by emotional stress.

The communication feature implements preventive and reactive behaviours. The participants highlighted its life-saving characteristic as the most important one of this feature. The ability of including several people with different roles was also considered as very important. One of them pointed out that this feature would help carers to have a more normal life knowing that they will be alerted if something bad happens. The points for improvement suggested by the participants are: adding the relationship (e.g. mother, father, partner) of the person to involve, delivering emergency alerts that overrule the silent mode of the phones, triggering emergency calls automatically, validating the contact information for being sure that the alerts will be delivered, and using other messaging services like Facebook messenger or Skype.

The medication reminder feature was considered as relevant for those without the habit of taking their medication properly. Nevertheless, it was perceived as an important feature to include. The fact that medication not only related to asthma can be added was recognised as positive, as well as its easiness to use. The most suggested improvement was related to confirming that the medication was taken. Some participants wanted to include the dosage of their medications, and keep an inventory allowing them to have reminders to buy medicine. Including diet management was highlighted as something important to add by one of the experts.

The virtual assistant feature was the lowest ranked. Participants perceived it as helpful for those who use this technology. However, only one of them affirmed to use virtual assistants regularly and recognised it as a technology that most people use nowadays. Four of them said that using a virtual assistant could be useful in some specific situations (like doing two things at the same time, not being able to use the screen or when their mobility is restricted). Although one said that it would be easier to use when having an attack, another one said that people cannot talk properly during an attack. In general, they agreed that this feature is good to have for those that want it.

Participants said that virtual assistants usually do not recognise their accent as a justification to avoid this technology. One participant suggested to ask the ACQ through the virtual assistant in order to have a better quality assessment. Moreover, two of them suggested to define a phrase that the virtual assistant can recognise as emergency, one recommended to use the VA to record a diary with the triggers and symptoms they experience. One extra question about the virtual assistant feature was asked, which referred to choose what the participants would prefer to use in order to keep track of their asthma health status. One chose to use virtual assistant only, two said they would use the ACAC only, and seven said they would use both options depending on the situation.

Feedback about the overall system was also collected. One question asked for improvements that were not specific to a feature. Some of these suggestions are: giving a name and a better icon to the mobile application, making all the collected data available to professionals/researchers, and adapting the prototype for people that take care of more than one person with asthma. Despite the fact that the questionnaire did not include a question asking about the positive points of the system, three of them wrote down comments that highlighted the mobile application as a solution covering all the key points they would like to manage about their asthma.

5.3 Chapter summary

Following the U-CIEDP, the validation of ADAPT included stakeholders of the asthma management process. They received a demonstration of a mobile application built based on the approach and then answered a questionnaire to evaluate the features of the prototype. These features were linked to the main elements of ADAPT. The participants were contacted through the Asthma UK Centre for Applied research.

The assessment made by the participants showed positive results. Following a Likert scale of five options to evaluate the usefulness of the features, all of them were assessed with average values that are between the two highest possible answers. The participants were also able to rank the features from the most important to the least important one. This was done in order to differentiate the perceived usefulness of the features that were assessed with similar values using the Likert scale. The points for improvements highlighted by the participants referred to non-fundamental issues that are mostly linked to the design of the mobile application.

Chapter 6

Discussion and conclusions

This chapter presents the discussion about the research project achievements and outcomes. The achievements of the research project are described based on the aims and objectives that were stated in section 1.4.1. Four points of view (personalisation, monitoring the location of the person with asthma, real-time analysis and predictions, and virtual assistant technology) are used to analyse the findings. The benefits, opportunities and challenges of the research work are outlined. Future work is also suggested in order to address some issues the proposal brings with it, and improvements for future applications. The discussion also highlights the technology that is required to allow the proposal to have a higher impact on the society.

Chapter 2 reports on the literature review that was done to identify the benefits and gaps of the existing context-aware solutions supporting asthma management (**A1-O1**). The *Interviews* and *Personalisation questionnaire* that were done as part of the initial stage experiments of the research project focused on gathering the insights of people with asthma and carers of people with asthma about using context-aware reasoning to support the asthma management process they were involved in. The outcomes of these experiments and its analysis, which were reported in section 3.2, linked the benefits of using context-awareness to support asthma management to the main concerns of the participants (**A1-O2**).

Chapter 4 reports on the main contribution of this research project, which is the Approach to Develop context-Aware solutions for Personalised asthma managemenT (ADAPT). The approach has been incrementally developed following the methodology reported in chapter 3. The final version of the approach that is reported in this thesis and its validation, which is reported in chapter 5, evidence the accomplishment of the objectives related to **A2**.

The mobile application that was used in the validation of ADAPT implemented features that relate to the elements of the approach. The outcomes of the validation were positive and encouraging to keep researching on the subject. The improvements that were suggested in the validation referred to non-fundamental issues, which is evidence to confirm the validity of ADAPT.

The case-based reasoning cycle for personalised asthma management is proposed and evaluated in section 4.3. This part of the proposal aims to provide support to people that are going through the uncertainty stage of asthma management. The evaluation of the case-based reasoning for personalised asthma management showed positive outcomes, which is considered as evidence to confirm that **A3-O1** was achieved. The interaction between the components implementing context-awareness and case-based reasoning, respectively, was proposed in section 4.3.4. This interaction, which is linked to **A3-O2**, was implemented in the prototype that was used in the validation of ADAPT, whose outcomes show that the participants were satisfied with the way this interaction was implemented. Although it was not possible to evaluate the interaction in a scenario where participants could assess it in their daily activities, the positive results of the validation are considered as evidence that the interaction proposed in this research project is accepted by the users.

The research work reported in this thesis accomplished its aims and objectives. Nevertheless, there are some points to highlight that should be considered in order to understand to what extend each of these aims and objectives were covered. Some of these points are then analysed from other points of view and as future work related to the research project in section 6.6. First at all, there is always the desire of involving as many participants as possible in the experiments with the aim of gathering more information. The number of people that took part in each experiment could have been higher, however, these numbers are satisfying considering the resources allocated to the research project. The collaboration formed with Asthma UK should be spotted as the key to success in involving people with asthma and carers of people with asthma in the experiments.

The inclusion of indoor environmental data in the experiments was a challenge to tackle. The integration of these data in the personalised monitoring feature implemented by the prototype was achieved at an experimental scale. The Smart Spaces Lab (Middlesex University), where this research project was done, is equipped with devices allowing to monitor temperature and humidity. These were used together with the Google Awareness and London

Air Quality Network APIs to feed the prototype with environmental data for the demonstration. The challenge also made it not possible to include indoor environmental data in the experiment done to evaluate the case-based reasoning cycle for personalised asthma management in a real-life setting because there were not enough resources to equip the indoor places the participants frequented and monitor their indoor exposure in real-time.

The communication feature, which includes the delivery of notifications, was assessed as very useful by all the participants that took part in the validation of the approach (chapter 5). Nevertheless, it must be pointed out that the notifications were not assessed in a scenario in which the participants could use the prototype for several days in their daily activities. The delivery of notifications is very important, so the personalisation of the notification component should be further investigated in a real-life setting. Finally, the virtual assistant implemented for the validation of ADAPT was one example of all the possible applications of virtual assistant technology for personalised asthma management. These applications should also be further investigated.

6.1 Personalisation

The main goal of the proposal is to support the development of context-aware solutions capable of addressing the heterogeneity of asthma condition management through personalisation. ADAPT supports this personalisation in different ways through the interaction of its different layers with the aim of providing services that can be customised depending on the necessities of the users. The case studies presented in this research work show that the proposal supports personalisation in a comprehensive way and at different stages of the asthma management process.

The use of the ADAPT context dimensions is a tool that can be used in the creation of solutions supporting personalised asthma management. Section 4.2 shows that these dimensions are able to describe people with asthma with different characteristics properly, which is important because it facilitates the design and delivery of useful services to the users. The use of the context dimensions is important in both the preventive and reactive states of a system supporting personalised asthma management. These dimensions help in the preventive state of the system to monitor the right indicators at the right places, and deliver warnings in the form of notifications to the right people. In the reactive state, the context dimensions allow to deliver emergency alerts to the right people, and to include proper information of an asthma episode (like location, exposure to triggers, medication usage, etc.) that can help in the decision-making process.

The context of a person with asthma is challenging to monitor because of the several places of interest that a person with asthma might like to include in the process. Although environmental monitoring technology is more reachable nowadays, it is still not common to have indoor monitoring devices connected as a network that can be used to get information from. Some commercial indoor environmental monitors are already in the market (e.g. see Ref. [88, 87]), however, their use is not generalised yet, and the availability of their data is not for public used. Hence, there is the need to create networks of monitoring devices that can provide environmental information about indoor and outdoor places. This would benefit people in general but especially those that suffer from respiratory conditions like asthma or COPD. It is important to highlight that, for being able to create this kind of networks, the integration challenge of context-awareness from an Internet of Things perspective [84] must be carefully addressed.

The interaction of context-aware reasoning and case-based reasoning to predict someone's asthma health status is another tool proposed to support the personalisation of asthma management. This part of the proposal aims to support people that do not know their triggers properly, which is common in people that are recently-diagnosed, changing the conditions they are exposed to, and whose asthma is evolving. The outcomes of the experiments that were done to assess this part of the proposal show positive results, despite of the fact that indoor environmental indicators were not possible to monitor and that the participants were asked not to stop their treatments.

The creation of a personal database of cases representing someone's previous experiences brings other potential challenge from a personalisation perspective. The frequency of bringing a new case to be assessed by the CBR is important to determine as it affects battery duration, and processing and storage capacity. It is also expected to affect the usability of the solution as users would stop using the solution if they are overloaded with useless notifications. This frequency is especially relevant to be defined when the database of cases is still not representative enough. The outcomes of the ACAC assessment suggest that this frequency should also be personalised by the user, however, they should be aware that the more cases they generate, the more accurate the case-based reasoning component will be.

6.2 Monitoring the location of the person

The location-tracking capability is very important to consider in the design and development of a solution implemented following ADAPT. Being capable of determining the accurate location of a person with asthma at a specific time directly impacts on the performance of the context-aware reasoning component of the solution. Moreover, the location also impacts the creation of the cases to be assessed by the case-based reasoning component.

The location context dimension is the one that operatively connects the information of the other context dimensions. Because of this, it is important that a system implementing ADAPT is carefully designed to determining the location of the person with asthma it supports as it highly impacts in the decision-making process. The location of the person at a specific time determines the exposure they have experienced then. Hence, it helps to distinguish the places that are a real hazard from those that are potential hazards. For instance, a person sensitive to pollen could consider a park they usually frequent as a place to monitor, however, if the person is currently at work, which is a place that is far from that park, then the system should present the park as a potential hazard when the pollen level is high there. On the other hand, if the person is walking nearby the park, then the system should present the park as a real hazard. This characterisation would not be possible to make if the system is not able to know the current location of the person.

The cases to be assessed by the case-based reasoning component have to be built considering the location context dimension as it is key to determining the real exposure experienced by a person with asthma. The cases are built based on the indicators that the context-aware reasoning component monitors. This monitoring process can be taking place at different locations (e.g. workplace, home, university, etc.) and, thus, it is important to know the places where the person has been in order to choose the right values of the indicators representing the potential triggers they have been exposed to. If the location is not included in this process, the cases will not then represent the exposure of the person with asthma and the accuracy of the case-based reasoning component will be affected.

The positive issue about this point is that the technology to track location through GPS is already established in the market, and it is broadly used in mobile technology. The experiment reported in section 4.3.3 successfully used this technology through the Google Awareness API [41] in order to keep track of the potential triggers the participants were exposed to. Nevertheless, technology for determining someone's indoor location is still not established in the market, despite the research efforts done on this subject (see, for example, Ref. [20, 110, 111]). This is not expected to be relevant in most of the cases but it would be useful for people spending relevant time in large indoor places that have rooms/areas with heterogeneous environmental characteristics.

6.3 Real-time analysis and predictions

ADAPT has been thought to facilitate the creation of solutions that support the decision-making process of asthma management by implementing services focusing on personalisation as the key aspect. Providing information that facilitates decision-making implies to deliver services allowing the analysis of past, present and future situations. ADAPT is able to address this issue putting special emphasis in the personalisation required for the implementation of asthma management plans.

The preventive state of a system implementing ADAPT should consider analysing the current and possible future contexts of a person with asthma. The current context can be analysed when the values of the indicators that are being monitored are available. For this, it is important to have access to the data provided by the devices monitoring the indicators the person with asthma is interested in. The analysis of possible future contexts is more complicated as it would required to have access to the forecasts of those indicators that are relevant to the person with asthma. Some of these forecasts are easy to access (e.g. weather forecast), however, there are others that are still not as reliable, broadly accepted and accessible (e.g. PM 2.5 or PM 10 forecasts).

The tools proposed in this article aim at supporting people with asthma that know and do not know their triggers properly. The way of supporting people knowing their triggers is less complex as their context analysis relies on the personalisation they do about the indicators they want to monitor. A set of if-else rules obtained from this personalisation are used to perform the real-time analysis and predictions. When it comes to support people not knowing their triggers properly, the case-based reasoning component supporting the real-time analysis and predictions needs to be capable of dealing with not enough information to complete the cases to evaluate.

Dealing with incomplete information is highly possible to happen in a real scenario implementing the tools proposed in this research work. Incomplete information is an issue because it increases the uncertainty and affects decision-making at every level. Nevertheless, this situation is easier to handle when a system implementing ADAPT supports people knowing their triggers. In this case, the system can show the analysis that it is able to make based on the if-else rules and the available information it has. For instance, if the system is not able to obtained the forecast of the temperature for the next day, it can then make predictions based on the available forecasts and inform users about the unavailable data.

The case-based reasoning component must be designed in order to know what to do when there is not enough information to complete a case. The system should know what to do with an incomplete case. This should be further investigated but some options are suggested here. One is to replace the missing values with historical information. Another is to not analyse the incomplete case, informing the user that there is not enough information to make a prediction. The third one is to do the similarity assessment of the case-based reasoning algorithm considering only the indicators with non-nullified values of the new case to analyse.

A system implementing ADAPT considers that a person with asthma should be able to create cases at any time. This is challenging because the system needs to define the timeframe for gathering the information that will be used to create a case. This decision depends on several factors. One of them is the time that has passed since the last time the user assessed their asthma health status. For instance, if the person has not assessed their asthma in two days, the system should not consider those two days as the timeframe to create the new case. It is better to consider the context related to the day of the assessment. If the assessment is early in the morning it should consider the night exposure of the person to create the case. The most important idea to keep in mind in this situation is the fact that a case should be made of the asthma health status of the person and the conditions that led to that health status. Hence, the timeframe should be defined considering that the case should represent reality in the most possible accurate way.

6.4 Virtual assistant technology

Virtual assistant technology is considered by ADAPT as an alternative that can facilitate the interaction with the user. This research work studies the use of this technology for the specific task of determining the health status of the person with asthma, in which virtual assistant technology is use as an alternative to the ACAC. The complementary nature of a virtual assistant is represented in Figure 4.1 by the dotted-lines rectangle that is positioned between the system and the user. The case study presented in section 4.4 refers to how virtual assistant technology can aid in the interaction represented by the arrow going from the *User* to the *Contextual Data* repository.

The outcomes of the validation of ADAPT (chapter 5) shows that, in general, people welcome the use of virtual assistant technology in asthma management, however, there is still some scepticism about it. The positive points are mostly highlighted by ideas that are associated with making a system more practical and easier to use in their daily activities. The scepticism is reflected by opinions that are linked to people not trusting in the virtual assistant capability to understand them, and people not being used to interact with a system through a virtual assistant. This supports ADAPT proposal of using virtual assistant as a complementing technology.

The application of virtual assistant technology studied in this research project is linked to a crucial task in asthma management, which is to keep track of the health status of the person with asthma. This, combined with the fact that the proposal aims to help people to deal with a chronic condition, gave the participants the right idea about the relevance of the tasks that a fully operative virtual assistant is meant to support. Most of them perceived as encouraging the fact that *"people are already using virtual assistant technology for less important things"*. One of them showed concern about *"there being too many variables for the virtual assistant to understand what is going on"*, while another expressed that *"a virtual assistant would be useful if it can recognise their speech, which might sound different in an emergency situation"*.

The virtual assistant is suggested as a tool complementing the context-awareness and case-based reasoning components of ADAPT, which are the fundamental elements of the proposal. Participants providing comments about the use of virtual assistant technology in asthma management highlighted the complementary characteristic of this technology by them stating that *"it would need to be linked with the personal asthma action plan"* or *"I would like to tell my peak flow (...) and what affected the need of any additional puffs, like environmental and consumables"*, or them asking if *"the virtual assistant is able to store biometric data"*.

6.5 Conclusions and contributions

The research work reported in this thesis studied the use of context-awareness as an appropriate concept aiding the creation of solutions supporting the asthma management process in a personalised way. This personalisation aims to address the heterogeneity of the condition, which is its most challenging characteristic. The gaps that are addressed in this research work were defined based on the outcomes of the literature review reported as part of the state-of-the-art and the experiments involving people with asthma and carers of people with asthma that were done as part of the research project.

The contributions of the study are presented as the Approach to Develop context-Aware solutions for Personalised asthma managemenT (ADAPT), whose elements and validation has been reported throughout the thesis. The context dimensions of ADAPT address the creation of solutions whose features can be customised depending on the characteristics of the person with asthma to support. The case-based reasoning component of ADAPT aims to aid asthma management when the person with asthma does not know their triggers properly, so they cannot customise their monitoring process because of the lack of knowledge about their condition. Virtual assistant technology is considered in ADAPT as a complementing technology that can enhance the human-computer interaction of a solution supporting asthma management.

The context dimensions proposed in ADAPT define the behaviour of the personalisation layer of a system that is built based on the approach. These context dimensions can be used as a path to follow in the development of context-aware solutions supporting personalised asthma management. Given the fact that ADAPT context dimensions were defined based on the interaction with stakeholders of the asthma management process and the literature review that was done as part of the research project, they can also be used as a guide showing other researchers the key points to focus future research on the area.

The study of case-based reasoning to support people going through the uncertainty stage led to the development of the case-based reasoning cycle for personalised asthma management. To the best of our knowledge, no research focusing on providing support in the uncertainty stage has been previously done. This part of the proposal was evaluated with synthetic data and in a real scenario involving people with asthma. For the last one, the Asthma Control Assessment Component (ACAC) was developed and validated for it to be used as the tool to determine the asthma health status of the participants during the experiment. This was critical to complete the case-based reasoning cycle for personalised asthma management.

The nature of ADAPT, which aims at supporting personalised asthma management comprehensively, motivated the study of the interaction between context-awareness and case-based reasoning. This part of the contribution addresses the lack of formalisation about this interaction in intelligent environments, which are thought to be enriched with several context-aware features that are achieved using different techniques. Thus, a way of matching the context-aware component of ADAPT with the case-based reasoning cycle for personalised asthma management was proposed and validated.

The inclusion of virtual assistant technology in ADAPT was motivated by the outcomes of the literature review and the interaction with stakeholders of the asthma management process, who showed interest in using this technology to facilitate their daily activities. Virtual assistant technology was studied as a complementary technology that can be used by those that are comfortable with it. The case study of this research project developed and validated a virtual assistant that can be used as an alternative to the ACAC in order to define the asthma health status of a person.

This thesis reports on the contributions of the associated research project. The evaluation and validation of the proposal was done under the framework of the User-Centric Intelligent Environments Development Process, which was possible to achieve thanks to the collaboration formed with Asthma UK. The main contribution of this work can therefore be summarised as follows:

- A literature survey discussing the existing context-aware supporting asthma management.
- The definition of ADAPT context dimensions, which are used to characterise the context of a person with asthma.
- The case-based reasoning cycle for personalised asthma management as the tool able to provide support to people going through the uncertainty stage of asthma management.
- The study of the interaction between context-aware reasoning and case-based reasoning in the development of intelligent environments supporting personalised asthma management.
- The study of virtual assistant technology to enhance the HCI component of solutions supporting personalised asthma management.

6.6 Future work

ADAPT is thought to aid the development of systems with what can be considered as future generation characteristics. As it has been explained through the whole thesis, several advances in different fields must be achieved before this kind of systems are able to spread significantly. Networks of indoor and outdoor environmental monitoring devices granting access to their collected data, hardware and software integration challenges, and mobile devices monitoring physiological indicators are some of the issues that need to be addressed in order to spread the technology this research work proposed to use to support asthma management. The case studies of this research project have been possible to complete because they have taken place in a city with accessible environmental monitoring data (London) and in a laboratory with enough resources (Smart Spaces Lab - Middlesex University).

The experiment assessing the behaviour of the case-based reasoning component did not include indoor environmental indicators at the indoor places the participants frequented because these places did not have the required equipment installed. Hence, although it is supposed that the accuracy of the case-based reasoning should improve if indoor environmental indicators are included in the cases, this should be explored in the future. The delivery of alerts from the case-based reasoning component should also be further investigated in a real scenario. This was not possible to achieve in this research project because the asthma health status of some people worsens when their stress level increase. Thus, it was considered better, from an ethical point of view, not to risk the participants because it was the first time the case-based reasoning component was tested in a real scenario.

The similarity assessment among cases that was done in the *retrieval* stage of the case-based reasoning cycle for asthma management (Fig. 4.3) directly affects the accuracy and should be further investigated. This research work used the Nearest Neighbour algorithm to retrieve the most similar previous case to the one that was being assessed. Although the results of the experiment were positive, it is suggested to explore other algorithms that may improve this accuracy. The Nearest Neighbour algorithm was chosen because of the good results that it showed when the case-based reasoning cycle for personalised asthma management was tested with synthetic data (see section 4.3.2).

ADAPT helps the collection of data that can be exploited through machine learning. One of the main motivations for using case-based reasoning is that there is not enough data about people going through the uncertainty stage. However, the use of case-based reasoning also aids in generating data that can later be processed with machine learning techniques to obtain meaningful information about people going through the uncertainty stage. The use of ADAPT context dimensions also generates data that hide relevant information about the asthma management process. Thus, the application of machine learning techniques to exploit the data collected and generated by solutions built based on ADAPT should be further investigated. This application should aim at discovering relevant information about people with asthma that could help to improve personalised asthma management.

The feedback that was obtained from the validation of ADAPT provides several points for improvement that should be further investigated. Concerns about cybersecurity and privacy were constantly raised by the participants during the experiments. This must always be taken into account in the development of solutions supporting personalised asthma management. The importance of this is related to the fact that solutions built based on ADAPT are expected to manage personal and sensitive data, so the proper measures should be implemented. A clear example of this is the monitoring of the users' location, which plays a very important role to define the location context dimension. Another important point highlighted by the participants was the delivery of more specialised reports, which brings the idea of including a data analytic component in ADAPT. This must be investigated in the future, especially when enough data to use in data analytic processes are collected.

This research work studied one of the many applications of virtual assistant technology for personalised asthma management. Participants suggested several practical applications of virtual assistant in asthma management. Some of them are: replacing the paper-based peak flow and medication diary, keeping track of what someone thinks has affected them, reminders of to-do tasks regarding the management of their asthma, and providing advices when the system detects the appearance of symptoms or concerning situations. The application of this technology was pointed out as more convenient for people living alone, with problems to remember things, and those recently-diagnosed that need more guidance in their initial stage.

The near future looks encouraging from a technological perspective. Several advances in different research areas are allowing the development of solutions with technological characteristics that few could have imagined in the near past. A future vision of the technology supporting personalised asthma management contemplates the spread of physiological monitoring equipment, the deployment of accessible monitoring indoor and outdoor environmental networks, as well as the automatic collection and integration of these data considering the customisation done by each user. This customisation must also drive the automatic real-time analysis of the data and predictions that trigger notifications in personalised formats and means to the right information recipients and at the right times. Further, the application of data analytic techniques to exploit the collected data and obtain meaningful information that can benefit asthma management is also part of this future vision. The human factor must be the most important one to be considered in order to achieve this vision. This progressive achievement, in which research on technology adoption and acceptance plays a key role, must take into account the main needs of people affected by asthma. They should be the ones showing the path to follow to the researchers that are willing to provide them with tools supporting the asthma management process in which they are involved.

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Core contributions

1 Quinde, M., Khan, N., Augusto, J.C., van Wyk, A., Stewart, J.: Context-aware solutions for asthma condition management: a survey. Universal Access in the Information Society. Springer (2018). https://doi.org/10.1007/s10209-018-0641-5.

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Appendix A: Questionnaire for the interviews

Interview for asthma patients

Participant ID Code: ________________________

1. Classifying information
    a. Age:
    b. Gender:
    c. How long have you been suffering from asthma?
    d. Severity of asthma:
    e. Which are your allergies?
    [Triggers - internal or external factors - provoking your asthma attacks (exacerbations)]
    f. Which are your symptoms?
    g. Which are the practices you consider as good (effective) to manage your condition?
    h. Which are the practices you consider as bad to manage your condition?

2. Application of context-awareness to support asthma management
    a. Explanation of context-awareness
    b. Do you think context-awareness can be used to support asthma management?
    c. How do you think context-awareness solutions can help you to manage your condition?
    d. What do you think a mobile application tracking your indicators should do to help you to manage your condition?
       [Which services/functionalities offered by a solution tracking your indicators do you think can be useful to help you to manage your condition?]
    e. Which are the indicators you think should be tracked to help you to manage your condition?
       [Use example of diabetes: blood glucose level]
    f. Who do you think should have access to this information (indicators)?

3. Application of Virtual Assistance (VA) awareness to support asthma management
    a. Explanation of VA.
    b. Do you think VA can be used to improve asthma management?

    c. How do you think VA can be used to improve asthma management?

    d. In which situations do you think VA can be useful to support a patient's asthma management?
       [What would you ask to a VA in order to improve the management of your asthma?]
       [What would you like a VA to say (without asking anything) in order to improve the management of your asthma]

4. Notification component
    a. Explanation of the concept of notification component
    b. Which notifications would you like to receive from a technological solution tracking your indicators?
    c. Which notifications should a technological tracking your indicators send to your carers?
    d. Which people/institutions do you think should be included as recipients of notifications?
    e. Which notifications would you like send to these people/institutions?
    f. Who do you think are the main stakeholders in your asthma management process? Why do you consider them as stakeholders?
    g. In case of an imminent asthma attack or respiratory arrest, who would you like to contact? Please, describe the role of the person/organization you would like to contact and explain which information you would like to send them.

5. Other questions
    a. How do you think carers would benefit from using this type of technology?

    b. Which negative effects do you think a solution tracking indicators of asthma patients may bring?

    c. Which negative effects do you think a solution implementing VA to support asthma management may bring?

Appendix B: Personalisation questionnaire

Personalisation questionnaire – people with asthma

Classifying information

1. Age:

2. Gender:

3. When were you diagnosed with asthma?

4. Severity of asthma:
    a. *Mild*
    b. *Moderate*
    c. *Severe*
    d. *I don't know*

5. Which are your triggers?
   [Answer as many as that applies to you]

    - A cold
    - Flu
    - Dust
    - House dust mites
    - Animals fur/feathers
    - Cockroaches
    - Mould
    - Fungi
    - Cigarette smoke
    - Open fires
    - Carpets
    - Furniture
    - Products used for decoration
    - Poor indoor ventilation
    - Damp weather
    - Dry weather
    - Cold weather
    - Hot weather
    - Sudden weather changes
    - Air pollution
    - Pollen
    - Alcoholic drinks
    - Strong emotions
    - Stress/Anxiety
    - Exercise
    - Cleaning products
    - Others:

    ____
    ____
    ____

6. Which are your symptoms?
   [Answer as many as that applies to you]
   - *Wheezing*
   - *Coughing*
   - *Tightness in the chest*
   - *Shortness of breath*
   - *Being too breathless to eat, speak or sleep*
   - *Breathing faster*
   - *Rapid heartbeat*
   - *Drowsiness*
   - *Confusion*
   - *Dizziness*
   - *Blue lips or fingers*
   - *Fainting*
   - *Nose feels scratchy*
   - *Throat feels scratchy*
   - *Others:*
     ____
     ____
     ____

Mobile application supporting asthma management

7. Which are the physiological indicators you think a mobile application supporting the management of your asthma should track?
   [Answer as many as that applies to you]
   - *Heart rate*
   - *Breathing rate*
   - *Sweat level*
   - *Oxygen level*
   - *Wheezing*
   - *Weight*
   - *Others:*
     ____
     ____
     ____

8. Which are the indoor environmental indicators you think a mobile application supporting the management of your asthma should track?
   [Answer as many as that applies to you]
   - *Temperature*
   - *Humidity*
   - *Dust*
   - *Dust mites level*
   - *Mould*
   - *Air pollution*
   - *Others:*
     ____
     ____
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9. Which are the outdoor environmental indicators you think a mobile application supporting the management of your asthma should track?
   [Answer as many as that applies to you]
   - *Temperature*
   - *Humidity*
   - *Dust*
   - *Dust mites*
   - *Mould*
   - *Air pollution*
   - *Pollen level*
   - *Others:*
     ____
     ____
     ____

10. Besides you, who should be able to access and check the information collected by this mobile application supporting the management of your asthma?
[Answer as many as that applies to you]
    - *Parents*
    - *Spouse or partner*
    - *Patient's doctor*
    - *Groups doing research on asthma*
    - *Only me*
    - *Others:* ______________________ ______________________ ______________________

11. Rate the following features/services/functions of a mobile application according to its importance in supporting the asthma management process of a person with asthma? Tick (✓) the correct number (0 means non-important and 5 means the most important).

Feature / Function / Service	**0**	**1**	**2**	**3**	**4**	**5**
Alerts regarding your triggers						
Alerts regarding your symptoms						
Notify someone in case of emergency						
Notify nearby asthma patients carrying medication in case of emergency						
Reports about the development of your triggers and symptoms.						
Instructions about how to act in case of emergency						
Map showing emergency centres near to your location						
Medication reminders						

12. What other features/services/functions do you think a mobile application supporting your asthma management process should have? Please, specify its importance (1-5).
____
____
____

13. Which people/institutions should receive notifications from this mobile application?
[Answer as many as that applies to you]
    - *Parents*
    - *Spouse or partner*
    - *Patient's doctor*
    - *Patient's nurse*
    - *Emergency department:*
    - *Others:* ____

14. In case of an asthma attack or an imminent respiratory arrest, who would you like to contact? How would you like to contact them?
Tick (✓) the most convenient combination of contact and way of contacting that applies to you.
[Answer as many as that applies to you]

Contact	I do not want to contact this person	SMS	Other messaging service (WhatsApp, Facebook Messenger, Telegram, etc.)	Notification (Alert) on the phone of the person to contact	Other
Parents					
Spouse or partner					
Your doctor					
Your nurse					
Emergency department					
Other:					
Other:					
Other:					

15. Who else would you like to contact in case of an asthma attack or an imminent respiratory arrest? How would you like to contact them?
____
____
____

16. In case of an asthma attack or an imminent respiratory arrest, which information would you like to send to the person you would like to contact?
[Answer as many as that applies to you]
- Location
- Details of the emergency
- Contact information
- I do not want to contact anyone.
- Other:
____
____

Other questions

17. How do you think that people involved in the asthma management process would benefit from using a mobile application offering these functions/services?
____
____
____
____
____

18. Which negative effects do you think a mobile application offering these functions/services may bring?

____
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Personalisation questionnaire - carers

Classifying information

1. Age:

2. Gender:

3. When was the person you take (took) care of diagnosed with asthma?

4. Severity of their asthma:
    a. *Mild*
    b. *Moderate*
    c. *Severe*
    d. *I don't know*

5. Which are their triggers?
   [Answer as many as that applies to you]

    - A cold
    - Flu
    - Dust
    - House dust mites
    - Animals fur/feathers
    - Cockroaches
    - Mould
    - Fungi
    - Cigarette smoke
    - Open fires
    - Carpets
    - Furniture
    - Products used for decoration
    - Poor indoor ventilation
    - Damp weather
    - Dry weather
    - Cold weather
    - Hot weather
    - Sudden weather changes
    - Air pollution
    - Pollen
    - Alcoholic drinks
    - Strong emotions
    - Stress/Anxiety
    - Exercise
    - Cleaning products
    - Others:

    ____
    ____
    ____

6. Which are their symptoms?
   [Answer as many as that applies to you]
   - *Wheezing*
   - *Coughing*
   - *Tightness in the chest*
   - *Shortness of breath*
   - *Being too breathless to eat, speak or sleep*
   - *Breathing faster*
   - *Rapid heartbeat*
   - *Drowsiness*
   - *Confusion*
   - *Dizziness*
   - *Blue lips or fingers*
   - *Fainting*
   - *Nose feels scratchy*
   - *Throat feels scratchy*
   - *Others:*
     ____
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Mobile application supporting asthma management

7. Which are the physiological indicators you think a mobile application supporting the management of their asthma should track?
   [Answer as many as that applies to you]
   - *Heart rate*
   - *Breathing rate*
   - *Sweat level*
   - *Oxygen level*
   - *Wheezing*
   - *Weight*
   - *Others:*
     ____
     ____
     ____

8. Which are the indoor environmental indicators you think a mobile application supporting the management of their asthma should track?
   [Answer as many as that applies to you]
   - *Temperature*
   - *Humidity*
   - *Dust*
   - *Dust mites level*
   - *Mould*
   - *Air pollution*
   - *Others:*
     ____
     ____
     ____

9. Which are the outdoor environmental indicators you think a mobile application supporting the management of their asthma should track?
   [Answer as many as that applies to you]
   - *Temperature*
   - *Humidity*
   - *Dust*
   - *Dust mites*
   - *Mould*
   - *Air pollution*
   - *Pollen level*
   - *Others:*
     ____
     ____
     ____

10. Besides them, who should be able to access and check the information collected by this mobile application supporting the management of your asthma?
[Answer as many as that applies to you]
   - *Parents*
   - *Spouse or partner*
   - *Patient's doctor*
   - *Groups doing research on asthma*
   - *Only me*
   - *Others:* ________________________
     ____
     ____

11. Rate the following features/services/functions of a mobile application according to its importance in supporting the asthma management process of a person with asthma?
Tick (✓) the correct number (0 means non-important and 5 means the most important).

Feature / Function / Service	**0**	**1**	**2**	**3**	**4**	**5**
Alerts regarding your triggers						
Alerts regarding your symptoms						
Notify someone in case of emergency						
Notify nearby asthma patients carrying medication in case of emergency						
Reports about the development of your triggers and symptoms.						
Instructions about how to act in case of emergency						
Map showing emergency centres near to your location						
Medication reminders						

12. What other features/services/functions do you think a mobile application supporting their asthma management process should have? Please, specify its importance (1-5).
____
____
____

13. Which people/institutions should receive notifications from this mobile application?
[Answer as many as that applies to you]
   - *Parents*
   - *Spouse or partner*
   - *Patient's doctor*
   - *Patient's nurse*
   - *Emergency department:*
   - *Others:* ____

14. In case of an asthma attack or an imminent respiratory arrest, who do you think should be contacted? How would you like them to be contacted?
Tick (✓) the most convenient combination of contact and way of contacting that applies to you.
[Answer as many as that applies to you]

Contact	I do not want to contact this person	SMS	Other messaging service (WhatsApp, Facebook Messenger, Telegram, etc.)	Notification (Alert) on the phone of the person to contact	Other
Parents					
Spouse or partner					
Your doctor					
Your nurse					
Emergency department					
Other:					
Other:					
Other:					

15. Who else should be contacted in case of an asthma attack or an imminent respiratory arrest? How would you like to contact them?
____
____
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16. In case of an asthma attack or an imminent respiratory arrest, which information should be sent to the person to contact?
[Answer as many as that applies to you]
- o Location
- o Details of the emergency
- o Contact information
- o I do not want to contact anyone.
- o Other: ______________________ ______________________

Other questions

17. How do you think that people involved in the asthma management process would benefit from using a mobile application offering these functions/services?
____
____
____
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____

18. Which negative effects do you think a mobile application offering these functions/services may bring?

____
____
____
____
____

Appendix C: ACAC evaluation questionnaire

ACAC evaluation questionnaire

1. How useful is it to analyse previous risky situations in order to predict future scenarios that may affect the health status of a person with asthma?

Very useless	Useless	Neutral	Useful	Very useful

2. How often should the mobile application show a notification asking you to complete the *asthma control assessment*?

____

____

3. Did the mobile application give you enough information to complete the *asthma control assessment*?

Very insufficient	Insufficient	Neutral	Plenty	Very plenty

4. Did the mobile application give you enough information to know that you had completed the *asthma control assessment*?

Very insufficient	Insufficient	Neutral	Plenty	Very plenty

5. How easy was it for you to learn how to perform the *asthma control assessment* through the mobile application?

Very difficult	Difficult	Neutral	Easy	Very easy

6. How easy is it for you to remember how to use the mobile application to do the *asthma control assessment*?

Very difficult	Difficult	Neutral	Easy	Very easy

7. How fast do you think it is to do the *asthma control assessment* through the mobile application?

Very slow	Slow	Neutral	Fast	Very fast

8. How confident did you feel when you did the *asthma control assessment* through the mobile application?

Very unconfident	Unconfident	Neutral	Confident	Very confident

9. Assess the following characteristics of the system:

	Very bad	Bad	Neutral	Good	Very good
Design of the screen / Interface					
Ease to use / User friendliness					

10. What improvements would you do to the system?

Appendix D: VA evaluation questionnaire

Questionnaire to develop a Virtual Assistant supporting people with asthma

The aim of this questionnaire is gathering information that will be used as the basis to create a Virtual Assistant that is able to help people with asthma.

You have been chosen to answer this questionnaire because you have been diagnosed with asthma. The estimated time to answer the questionnaire is 10 – 15 minutes.

The collected data will be used for research purposes. It will not be used for commercial purposes. No personal data nor sensitive data is collected. Completion of this anonymous questionnaire is deemed to be your consent to take part in this research.

We want to create a Virtual Assistant that is able to help people with asthma. A Virtual Assistant *"can interpret human speech and respond via synthesized voices. Apple's Siri, Amazon's Alexa, Microsoft's Cortana, and Google's Assistant are the most popular voice assistants and are embedded in smartphones or dedicated home speakers. Users can ask their assistants questions, control home automation devices and media playback via voice, and manage other basic tasks such as email, to-do lists, and calendars with verbal commands."*
These are links to some videos on YouTube illustrating how a Virtual Assistant works:

- Google's Assistant: www.youtube.com/watch?v=FPfQMVf4vwQ
- Apple's Siri: www.youtube.com/watch?v=7fZYqDP1WgM
- Microsoft's Cortana: www.youtube.com/watch?v=DxrJWSi_IWo
- Amazon's Alexa: www.youtube.com/watch?v=FQn6aFQwBQU

The definition of Virtual Assistant was extracted from:
Matthew B. Hoy (2018) Alexa, Siri, Cortana, and More: An Introduction to Voice Assistants, Medical Reference Services Quarterly, 37:1, 81-88, DOI: 10.1080/02763869.2018.1404391

Please, answer the following questions that will help us to design a Virtual Assistant that will be able to support people with asthma in their asthma management process.

1. Classifying information

1.1. Age:

1.2. When were you diagnosed with asthma?

1.3. Severity of your asthma:

a. Mild
b. Moderate
c. Severe
d. I don't know

1.4. When was your last asthma attack?
- I have never had one
- Less than 1 year ago
- 1 year ago
- 2 years ago
- 3 or more years ago

2. Virtual Assistant supporting asthma management

2.1. What phrases would you use to tell someone that you are feeling well with regard to your asthma symptoms?
[Write as many as you can]
____
____
____

2.2. What phrases would you use to tell someone that you are not feeling well with regard to your asthma symptoms (NOT an emergency situation)?
[Write as many as you can]
____
____
____

2.3. What phrases would you use to tell someone that you are having an asthma attack (emergency situation)?
[Write as many as you can]
____
____
____

3. Other questions

3.1. What would you like the Virtual Assistant to do after you saying that you are feeling well with regard to your asthma symptoms?
____
____
____

3.2. What would you like the Virtual Assistant to do after you saying that you are not feeling well with regard to your asthma symptoms (NOT an emergency situation)?
____
____
____

3.3. What would you like the Virtual Assistant to do after you saying that you are having an asthma attack (emergency situation)?

____
____
____

3.4. Please, give us your comments with regard to using a Virtual Assistant to support asthma management.

____
____
____

Appendix E: ADAPT validation questionnaire

Questionnaire *(Participant Code___________)*

Project title: Approach to develop context-aware solutions for personalise asthma management

Completion of this questionnaire is deemed to be your consent to take part in this research.

Personalised monitoring feature

1. How useful do you think it is the system allowing you to personalise the indicators that you want to monitor at your places of interest?

Very useless	Useless	Neutral	Useful	Very useful

Please, explain why.

2. How would you improve the way the system allows you to personalise the indicators that you want to monitor at your places of interest?

Communication feature

3. How useful do you think it is the system allowing you to choose the people that you want to involve in your asthma management plan and their roles?

Very useless	Useless	Neutral	Useful	Very useful

Please, explain why.

4. How would you improve the way the system allows you to choose the people that you want to involve in your asthma management plan and their roles?

Triggers assistance feature

5. How useful do you think it is the system helping you to detect dangerous situations based on your previous health deterioration experiences?

Very useless	Useless	Neutral	Useful	Very useful

Please, explain why.

6. How would you improve the way the system helps you to detect dangerous situations based on your previous health deterioration experiences?

Control test feature

7. How useful do you think it is it the system keeping record of your asthma control test results?

Very useless	Useless	Neutral	Useful	Very useful

Please, explain why.

8. How would you improve the way the system keeps record of your asthma control tests?

Virtual assistant feature

9. How useful do you think it is the system giving you the option of using a virtual assistant to interact with it?

Very useless	Useless	Neutral	Useful	Very useful

Please, explain why.

10. What would you prefer to use in order to keep track of your asthma health status?

Virtual assistant only	Both	Control test only

Please, explain why.

11. How would you improve the way the system uses a virtual assistant to keep record of your asthma health status?

Medication reminder feature

12. How useful do you think it is it the system allowing you to set medication reminders in order to help you in the management of your asthma?

Very useless	Useless	Neutral	Useful	Very useful

Please, explain why.

13. How would you improve the way the system allows you to set medication reminders in order to help you in the management of your asthma?

Overall system

14. Order the features of the system from the most important (1) to the least important (6).

Features:

- Personalisation
- Communication
- Triggers assistance
- Control test
- Virtual assistant
- Medication reminder

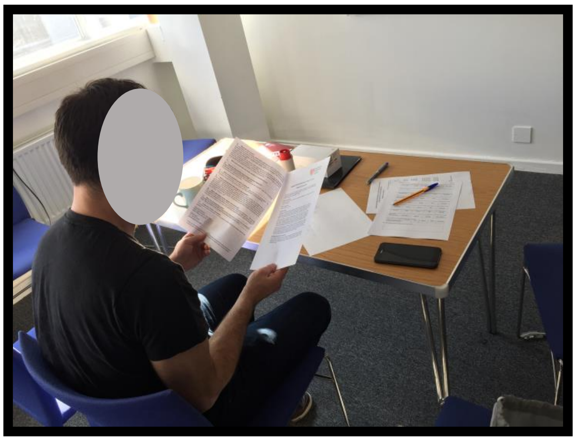
Order:

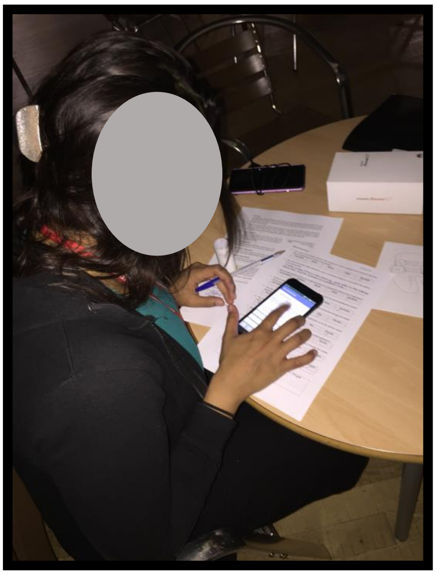
(1)	
(2)	
(3)	
(4)	
(5)	
(6)	

15. What would you improve about the system?

Appendix F: ACAC evaluation and ADAPT validation photos

ADAPT: Asthma Control Assessment Component usability evaluation photos





ADAPT: Photos of the validation