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

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Abstract

People with asthma have heterogeneous triggers and symptoms, which they need to be aware of in order to implement the strategies to manage their condition. Context-aware reasoning has the potential to provide the personalisation that is required to address the heterogeneity of asthma by helping people to define the information that is relevant considering the characteristics of their condition and delivering services based on this information. This research work proposes the Approach to Develop context-Aware solutions for Personalised asthma managemenT (ADAPT), whose aim is to facilitate the creation of solutions allowing the required customisation to address the heterogeneity of asthma. ADAPT is the result of the constant interaction with people affected by asthma throughout the research project, which was possible to achieve thanks to the collaboration formed with the Centre for Applied Research of Asthma UK. ADAPT context dimensions facilitate the development of preventive and reactive features that can be configured depending on the characteristics of the person with asthma. The approach also provides support to people not knowing their triggers through case-based reasoning and includes virtual assistant as a complementing technology supporting asthma management. ADAPT is validated by people with asthma, carers and experts in respiratory conditions, who evaluated a mobile application that was built based on the approach.

Keywords: context-aware reasoning, case-based reasoning, virtual assistant, asthma management, personalisation, mobile health

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1. Introduction

Asthma is a chronic inflammatory disorder of the airways causing some symptoms in susceptible individuals that are usually linked to the widespread and variable airflow obstruction [1]. The Global Initiative for Asthma (GINA) defines asthma as a heterogeneous condition that is characterised by chronic airway inflammation and defined by the person's history of respiratory symptoms [2], like wheeze, breathlessness, chest tightness, and cough [2, 3]. There is no cure for asthma [4, 5] and its treatment is based on a management approach whose aim is to achieve control of the condition through pharmacological and non-pharmacological strategies [2, 3].

Personalisation is the key to implement asthma treatments that can address the heterogeneity of the condition. The heterogeneity of asthma means that people with asthma have different triggers provoking their attacks and that they experienced different symptoms when an attack occurs. Hence, there is no one-fits-all guideline for people with asthma, and their asthma management plans have to be customised considering the specific characteristics of their conditions [2, 3].

Context-aware reasoning (context-awareness or C-AR) can aid to support personaliSSation of asthma management plans [6]. In Ref. [7], context is defined as *"the information that is directly relevant to characterise a situation of interest to the stakeholders of a system"*. C-AR 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"*. Unlike Dey's definitions of context and context-awareness [8, 9] that go from the system to the user, these are more linked to a person-centric approach that goes from the user to the system.

This research work proposes and validates the Approach to Develop context-Aware solutions for Personalised asthma managemenT (ADAPT), which considers technology enhancing solutions aiming at supporting asthma management with a special focus on personalisation. ADAPT context dimensions allow the personalisation that is required to address the heterogeneity of asthma. The approach presents the interaction between C-AR and case-based reasoning (CBR) to provide support at a specific stage of asthma management in which people do not know their triggers properly. Virtual assistant technology is also suggested as a complementing technology to enhance the HCI component of solutions supporting personalised asthma management.

The article is divided in 9 sections. Section 2 presents the state-of-the-art of C-AR and CBR in asthma management. The application of both concepts are explained from a health care perspective. Applications of these concepts in asthma management are then described to show the existing gaps in the subject.

The methodology of the research project follows a user-centric approach whose aim is to include stakeholders in order to ensure a high acceptance degree of the proposal. Thus, the research tools and methods were chosen to gather the insights of people with asthma and carers of people with asthma during the several iterations done in the project. A collaboration with Asthma UK [10] was formed to involve people with asthma and carers that are part of their Patient Advisory Group. Section 3 provides more details about the methodology.

Section 4 explains ADAPT as a tool guiding the development of C-AR solutions supporting personalised asthma management. The approach is based on the lessons learned during the research project. The development-validation iteration cycle explained in the methodology allowed to gather the insights of people with asthma, carers and experts in respiratory conditions about the features they wish from a solution supporting asthma management. The evolution of ADAPT is described, highlighting the components a solution supporting personalised asthma management should have, and how each component supports the personalisation required to treat the condition. A real case study as an application example of using ADAPT is also presented.

The use of CBR as a complement of C-AR for personalised asthma management is presented and validated through a real case study in section 5. CBR is a type of artificial intelligence that simulates *"the use of old experiences to understand and solve new problems"* [11]. Its applications in the health sciences have shown promising results [12, 13]. Nevertheless, the application of CBR together with C-AR in the development of intelligent environments has not been explored in depth yet [14]. The main contribution presented in this section is the formalisation of the interaction between CBR and C-AR, and the real case study evaluating its application to provide support when people with asthma do not know or poorly know their triggers.

Section 6 explores virtual assistant (VA) as a complementing technology to support personalised asthma management. This section reports on the development of a VA that was designed to provide users with an alternative way of determining their asthma health status. The validation of the VA text classifier is presented. The VA is developed as an example that is then shown to real users in the validation of the approach.

The validation of ADAPT is presented in section 7, where details about the experiment involving people with asthma, carers and experts in respiratory conditions is explained. Although some features of the system that was developed to demonstrate ADAPT were previously evaluated as individual units, this section reports on the validation of the system as a whole.

Finally, section 8 and 9 expose the discussion and conclusions of the research work. The discussion mainly focuses on the benefits, opportunities and challenges that are analysed from different points of view. Future work is also suggested in order to encourage research on the subject.

2. State-of-the-art

This section presents the state-of-the-art of the application of C-AR and CBR in asthma management. The application areas of these concepts are described with application examples, putting a special emphasis on the application in the healthcare domain. The research efforts that have been made on using C-AR and CBR for asthma management are shown an analysed.

2.1. Context-aware reasoning

Intelligent Environment are built on pervasive and ubiquitous computing, smart environments and ambient intelligence [15]. C-AR is a relevant element of pervasive/ubiquitous computing [16] and ambient intelligence [17]. The application of C-AR, from an Intelligent Environments perspective, can be classified into transportation, education, production places, smart offices, ingelligent supermarkets, energy conservation, entertainment, and health [15]. The application of C-AR in health care, as part of ambient intelligence, can be classified into continuous monitoring, assisted living, therapy and rehabilitation, persuasive well-being, emotional well-being, and smart hospitals [17].

The development of technologies aiding to improve the quality and efficiency of healthcare is particularly important when it comes to treat chronic conditions because of the increasing amount of people suffering from them. It is essential to use a community-centred care paradigm focusing on a lifestyle management to prevent and cope with these conditions [18], and researchers are aware of the crucial role that technology plays in self-management [18, 19, 20]. From this perspective, C-AR can provide tools to support people suffering from chronic conditions [20, 21]. There are research works exemplifying the use of C-AR to support people suffering suffering from stress and anxiety [22], diabetes [23] and cardiovascular conditions [24].

2.1.1. *Context-aware solutions for asthma management*

Mobile applications supporting asthma self-management have been reviewed. Belisario et al. [25] showed that, although mobile application were potentially beneficial for asthma management, the use of this technology to support asthma self-management was still in its early days, which made it not possible to reach firm conclusions about the potential effect of asthma applications. Huckvale et al. [26] analysed the evolution of mobile applications for asthma, showing that the market landscape was made of low-quality generic information applications that do not focus on the gaps in asthma management. Wu et al. [27] highlighted 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.

Research on developing and validating technology to support asthma management at different stages have been done. Lefco et al. [28] study the use of icons in the design of asthma mobile health tools supporting parents of young children. Chamberlain et al. [29] propose a mobile platform able to diagnosed people suffering from asthma and chronic obstructive pulmonary disorder. MyAirCoach is a mobile application whose aim is to improve the education component of asthma management plans [30]. Grossman et al. [31] study the use of electronic monitoring devices to reduce usage of rescue medication by improving adherence to daily medication. The use of mobile applications supporting the asthma self-management responsibility transition from parents to adolescents has also been studied in Ref. [32].

A survey on solutions supporting asthma management shows that they do not address the personalisation that is required to implement asthma management plans [6]. It highlights that existing C-AR solutions supporting asthma management do not allow users to customise the indicators to monitor nor the features to use, considering the characteristics of their condition. The survey also shows that VA has not been studied as a technology to aid asthma management. As an attempt to close the personalisation gap, Ref. [33] proposes a classification of the indicators that should be monitored to facilitate the personalisation of asthma management.

2.2. *Case-based reasoning*

CBR as a research topic is gaining momentum [34, 35], and has been studied in several domains like legal reasoning, web services, and health sciences [36]. Successful application examples in the healthcare and industrial domains are shown in Ref. [36, 37], which highlight the flexibility of CBR as a benefit of the technique for being applied in fields where experiential knowledge is easy to collect and reuse. Examples of this flexibility are presented in Ref. [38] that studies CBR for maintenance panning, Ref. [39] that proposes Process-Oriented CBR to generate workflows from procedural texts, and Ref. [40] that identifies 17 construction management application fields where CBR have been used.

CBR has been applied in the health sciences from its beginnings [41, 42]. One of the reasons of this is the similarity between the CBR cycle and the decision-making process that is used in the health sciences [13, 41, 43, 44] where expert knowledge plays a major role, and evidence-based practice is generalised [45]. 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 [42].

Health sciences is a growing application research area for CBR [12, 13, 41, 42, 43, 45, 46]. CBR systems in the health sciences can be classified based on their purpose into diagnosis, classification, tutoring, planning, and knowledge acquisition/management systems [12, 47]. Hybridisation of CBR with other AI techniques to create multimodal reasoning systems is promising to handle large, complex and uncertain data in clinical environments [12, 43]. Ref. [48] presents an example of using CBR to identify eligible patients for clinical trials based on electronic health records (EHRs). The target patient for a trial is represented by a set of cases that are made based on the EHRs of patients that have already been enrolled for the trial. CBR is used to assess if someone is eligible for the trial. Another application example is a multi-agent architecture that can be adapted to support decision-making in many medical aspects of gastric cancer [49]. The architecture proposes CBR as a suitable technique for classification/diagnosis and choosing the most effective therapeutic strategy for a patient.

There are several application examples of CBR in healthcare. Bach et al. [50] show how it supports the decision-making process of selfBACK, a system aiding the management of non-specific low back pain. The system provides patient-specific recommendations for their low back pain treatment through the application of CBR. Ref. [51] presents a hybrid system using rule-based reasoning to improve the CBR process, which is used to simulate the general practitioner's behaviour and estimate the probability of a patient having a specific cancer. CBR has also been applied to support people suffering from chronic conditions. An example is given by Yuan et al. [52] who propose a system using CBR to predict the blood sugar level of a person with diabetes. Another example is Ref. [53] that proposes the use CBR to provide decision-support in stress management based on finger temperature signals.

2.2.1. *Case-based reasoning in asthma management*

CBR has been used in the development of the knowledge support system for asthma care services proposed in Ref. [54]. The system is meant to be used by inexperience 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 CBR to retrieve the case that is the most similar one to the patient, based on the input data. The selected case is then used to define the asthma care plan for the patient.

2.3. *Context-aware and case-based reasoning*

The use of C-AR together with CBR have been explored in different application areas. Kwon & Sadeh [55] propose the use of CBR to replace the buyers utility function in a multi-agent intelligent system aiding context-aware comparative shopping. Kumar et al. [56] also apply both concepts to e-commerce by building a recommendation engine based on two CBRs that stores users and products contexts, respectively. Zimmermann [57] uses CBR to provide recommendations to users in a museum guide C-AR system. MyMessage is a C-AR system using CBR as an alternative to the analytic hierarchy process in order to achieve message filtering [58]. Lee & Lee [59] use C-AR and CBR to improve the performance of a music recommendation system.

A recent survey on using C-AR together with CBR shows that, despite the potential synergies of using both concepts in the development of intelligent environments, there is a lack of research on the subject [14]. Leake et al. [60] describe the research opportunities of using CBR in smart homes, focusing on delivering personalised services. An example of using both concepts to develop ambient intelligence is given in Ref. [61], which reports on a system using CBR to achieve contextualised ambient intelligence. The system was validated in a hospital ward by configuring it to detect situations occurring there. Ospan et al. [62] provide another example by using both concepts to develop a virtual assistant that solves conflicts based on users' preferences in a smart home.

There is a lack of formal methodologies aiding the application of C-AR together with CBR in the development of intelligent environments. Khan et al. [14] show that the benefits of merging both concepts in intelligent environments outweight the challenges, but that no formal way of merging them has been proposed. Ref. [63] propose a hybrid framework for pervasive healthcare that uses fuzzy logic in the retrieval and adaptation stages of the CBR cycle. The framework was validated through a simulation in a smarthome laboratory but not using data from real users in a real scenario.

The analysis of the research works reviewed show that CBR and C-AR are usually merged in two ways. The first one is using CBR as the main process to achieve C-AR [56, 57, 59, 64, 61, 63]. The second one is using CBR 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 a C-AR feature [55, 58]. Nevertheless, there is a lack of research on formalising the use of CBR not only to achieve a desired context-aware service, but also to interact with other features that are similarly complex and important in the creation of a more comprehensive C-AR system. This is important because intelligent environments are expected to deliver several services that are achieved using different techniques in their logics.

Quinde et al. [65] suggest the use of CBR to support asthma management as a complementing technique to enhance the personalisation of C-AR systems supporting asthma management. CBR is used to provide support when people do not know their triggers properly by creating cases representing previous experiences that are used to attemp the prediction of their health status. Although the proposal was validated with synthetic data showing promising results [65], it has not been validated in a real life scenario with data obtained from real users.

The state-of-the-art presents the existing gaps in the creation of solutions supporting the required personalisation to implement asthma management plans. Another outcome of this section shows that C-AR and CBR can be used together to enhance the services provided by intelligent environments. Nevertheless, there is a lack of methodologies targeted to enhance the application of both concepts in the creation of intelligent environments. This is related to the lack of study on integrating both concepts in more comprehensive systems providing C-AR services using CBR, and others services not using CBR in their logic. ADAPT addresses these gaps by formalising and validating ADAPT context dimensions and its integration with CBR in the creation of solutions supporting personalised asthma management.

3. Methodology

The User-Centric Intelligent Environment Development Process (U-CIEDP) is the core of the methodology and, thus, the activities of the research project are explained under this framework. The U-CIEDP focuses on ensuring that the technology used to develop services closely match the requirements of users. The overall recipe for success of the U-CIEDP is acknowledging the human factor as the most influential one in the development of the technology. An example of its application is shown in Ref. [66], which illustrates how the U-CIEDP guided the development of smart technology for people with special needs. Chin et al. [67] recognise the U-CIEDP as a tool that 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. 1, which illustrates how the incremental contributions of the project were achieved through the involvement of the key stakeholders (people with asthma and professional/non-professional health carers) of the asthma management process. They were included during the whole project to gather their main insights about the technology. The circle tagged as *Stakeholders engagement* wraps the experiments that included interaction with these stakeholders. The circle *Scoping* refers to the feedback that was collected from the outcomes of the interaction with them. The analysis of these outcomes led to the development of ADAPT, which is properly explained in section 4. The *Main development* circle refers to the components that were developed and then added to the prototype (*Installation* circle) that was used in the validation of ADAPT (section 7). The elements shown in Fig. 1 were developed and improved incrementally, however, the arrows in the figure represent the processes that were more influential in the development of the elements of ADAPT. All the experiments had the approval of the Computer Science Research Ethics Committee of Middlesex University.

This article reports on the final outcomes of the research project illustrated in Fig. 1. The research project began with the *Literature survey*, whose outcomes have been summarised in section 2. The *Interviews* and *Personalisation questionnaire* aimed at collecting insights about the main concerns in asthma management and how C-AR could be used to address these gaps. These experiments were influenced by the *Literature survey*. People with asthma (4), carers (2) and one expert in respiratory conditions were interviewed. The *Personalisation questionnaire* was built based on the outcomes of the interviews and applied to 42 stakeholders. The collaboration with Asthma UK [68] was formed at this stage. The *personalisation questionnaire* was spread through their Patient Advisory Group, which is part of the Asthma UK Centre for Applied Research [10]. The main outcomes and more details of the *Personalisation questionnaire* can be found in Ref. [65, 69]. A summary of the outcomes of both experiments is shown in table 1.

The outcomes of the research project initial stage (*Literature survey, Interviews and Personalisation questionnaire*) highlighted the need of solutions supporting asthma management in a personalised way that can tackle the heterogeneity of the condition. This research work proposes ADAPT context dimensions as the tool allowing users to personalise the preventive and emergency features of a solution supporting their asthma management, considering health and non-health related characteristics of their condition. ADAPT context dimensions are explained in section 4.1. The initial stage also showed that C-AR cannot support by itself people not knowing or poorly knowing their triggers. This is common in recently-diagnosed people, when someone's asthma is evolving (i.e. their triggers and symptoms are changing), and when they are exposed to environmental characteristics they have not been exposed before. The stage in which people do not know their triggers will be referred to in this article as *the uncertainty stage*.

The article also reports on the experiment evaluating the use of CBR together with C-AR as a solution to address the *uncertainty stage* in a real life scenario. Although the CBR cycle for personalised asthma management has been presented in Ref. [65], the interaction between C-AR and CBR has not been formalised nor evaluated in a real life scenario before. Three participants (people with asthma) were asked to use a prototype that was able to create cases by associating their asthma health status with some environmental indicators they were exposed to. These cases were analysed by the CBR algorithm. Section 4.2 shows the description of the participants as an example of using ADAPT to provide a comprehensive description of their contexts. Section 5 provides more details about the experiment evaluating CBR & CAR in a real life scenario.

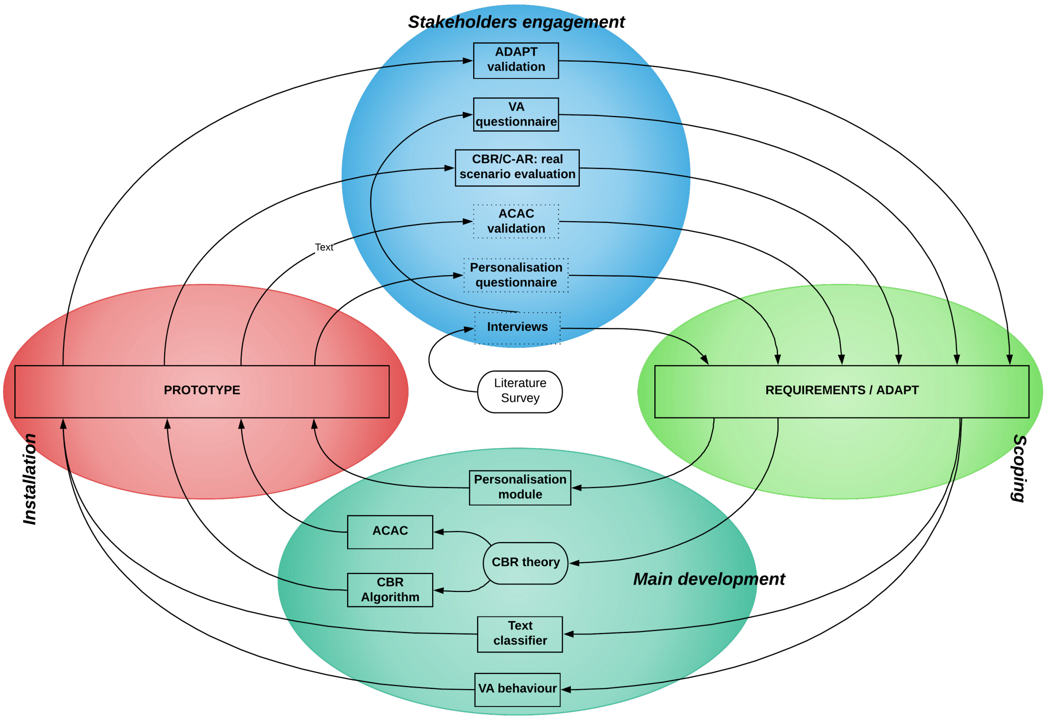


Figure 1: Methodology process based on the U-CIEDP

Table 1: Main outcomes of the interviews and personalisation questionnaire

Method	Outcomes
Interviews	✓C-AR solutions can address the personalisation required to implement asthma management plans. ✓Asthma heterogeneity is a concern, especially when the patients' triggers are not known properly. ✓People would choose the features to use depending on the characteristics of their asthma and on personal non-health related circumstances of the people involved in the management of their asthma. ✓The people/organisations related to someone's asthma management process must be considered in the information supply chain. ✓There is interest on exploring the use of virtual assistant in activities linked to asthma management. ✓Difficulties were experienced when people with asthma moved to a location with environmental characteristics they were not exposed before.
Pers. questionnaire	✓Respondents would like to have medication reminders, and reports and alerts as regards their triggers and symptoms as the main preventive features of solutions supporting asthma management. ✓Respondents would like a C-AR solution to provide them with instructions, notify their next of kin and to show a map with near emergency centres in case of emergency (reactive). ✓The people to contact and the preferred way of contacting them vary among the respondents. ✓Heterogeneity is an important factor to consider. It includes not only health-related characteristics of someone's asthma, but non-health related circumstances as well.

The study of VA as a complementing technology facilitating the daily activities of people affected by asthma is another highlight of this article. The *Literature survey* shows that the use of VA in asthma management has not been studied yet. The people interviewed in the initial stage showed interest in exploring the use of VA to support their asthma management. The examples given by the interviewees suggest they would use a VA in preventive and emergency situations. This article reports on the case study of a VA that interacts with people with asthma, and recognises if their health status is normal or deteriorated depending on the phrases they use. This outcome is stored as a record of their asthma health status. The text classifier is the core of the VA that was implemented for the case study. It was trained using synthetically generated phrases and classification algorithms from scikit-learn [70]. The evaluation of the text classifier 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 through the Asthma UK's Patient Advisory Group. This experiment is presented in section 6.

Following the U-CIEDP, the validation of ADAPT was done involving real users. Ten participants attended to an individual session in which a demonstration of the features of the mobile application implementing the proposal was done. They were then asked to provide their insights about the proposal through a questionnaire that was made of open and closed questions. More information of the validation is shown in section 7.

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

ADAPT has evolved as a natural consequence of using the U-CIEDP, which allowed the interaction with the stakeholders. The research work presented in Ref. [33] can be considered as the first version of ADAPT, although the approach was still not known as ADAPT by then. Ref. [33] suggested allowing users to choose the indicators and the places to monitor considering the characteristics of their condition. It proposed to classify the indicators to monitor into three types: Patient's Indicators, Indoor Environmental Indicators and Outdoor Environmental Indicators.

The first version of ADAPT was the first and a very important step towards the personalisation of asthma management. Before it, no efforts had been made on proposing technology addressing the required personalisation to undertake asthma heterogeneity. However, this version had to be improved. The first improvement refers to the classification and inclusion of the indicators a solution supporting personalised asthma management should consider in its logic. The classification of ADAPT first version did not include pharmacological strategies in the reasoning process. Moreover, the inclusion of the stakeholders of a person with asthma was very limited as it did not consider important details of the information supply chain (e.g. ways of contacting, information to send, stakeholders' roles). The use of location and time, which are key in the decision-making for personalised asthma management, were also not included. This article presents ADAPT context dimensions as one of the improvements of the approach.

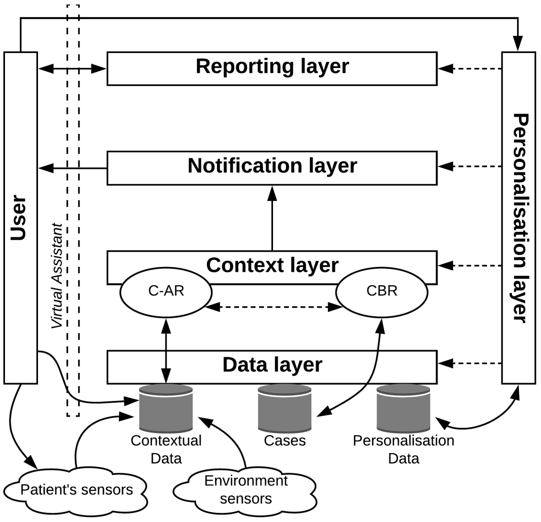


Figure 2: The high level architecture of a system built based on ADAPT

The other improvement is about ADAPT being able to provide support in the uncertainty stage. CBR was 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 are then used to assess hazardous situations. This has been added to ADAPT as an alternative to provide support to people with asthma going through the uncertainty stage. CBR brings other interesting issues to address in the development of C-AR solutions for personalised asthma management, which are link to the interaction between C-AR and CBR in the development of intelligent environments. These are explained in section 5.

Figure 2 shows a high level architecture diagram illustrating how ADAPT is used to create solutions supporting personalised asthma management. The *Personalisation layer* influences all the other layers of the system. The user interacts with the *Personalisation layer* to provide the system with their preferences that are stored as a profile in the *Personalisation database*, which is then queried by the *Personalisation layer* to define the behaviour of all the other ones. The personalisation is based on ADAPT context dimensions, which allow to customise the preventive and emergency features of the system. These dimensions are explained in section 4.1.

The overall system is influenced by the *Personalisation layer*. The *Data layer* collects the contextual data considering the profile delivered by the *Personalisation layer*. 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. The *Context layer* monitors the contextual data in real time, considering the monitoring process previously defined through the *Personalisation layer*. The *Notification layer* also performs considering the user's communication preferences. Finally, the *Reporting layer* shows the status of the indicators the user chooses to monitor in their profile.

The use of CBR for 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 are complementing 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 the person's asthma health status when they do 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*. A detailed explanation about this interaction is provided in section 5.

The interaction with the stakeholders brought another interesting feature to include in ADAPT, which refers to the use of a VA to support personalised asthma management. The VA feature of the system, which is represented by the dotted rectangle placed between the *User* box and the layers of the system in Fig. 2, is another contribution of ADAPT. It is 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 provide information to the *User*. Finally, the *User* can provide data to feed the *Contextual Data* through the VA that interprets how they are feeling. ADAPT considers all these applications of VA for personalised asthma management, however, this research work explores the development and validation of a VA than can be used to define the health status of a person with asthma for those users that are keen on using a VA. This is presented in section 6.

4.1. ADAPT context dimensions

The performance of the *Personalisation layer* (Fig. 2) is based on the information that is relevant for 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 was considered throughout the whole project, especially in the processes involving interaction with stakeholders. This article contributes to answering the question by presenting ADAPT context dimensions as the dimensions a solution shall be able to handle for providing users with a suitable tool allowing a personalised management of their asthma. These dimensions are shown in Fig. 3. The strongest relationships among these dimensions are represented by the arcs connecting them.

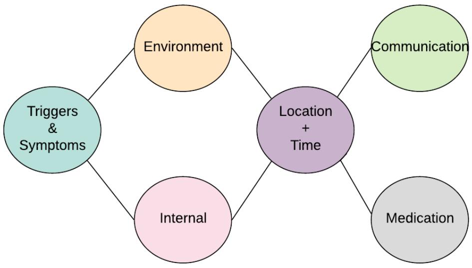


Figure 3: ADAPT context dimensions

The *Triggers & Symptoms* define what situations can lead a person to experience an attack, and what they present when an attack occurs. The identification of the triggers and symptoms of a person with asthma is difficult. Nevertheless, it is very important because it is the basis to define the proactive plans to avoid their triggers, and the reactive plans to follow when their 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 *Environment* refers to the environmental indicators to monitor 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 those they usually frequent but they could include others, like places they will visit. Flexibility in choosing the indicators to monitor at each place should be allowed as not all the places of interest have the same monitoring equipment available. For instance, a person 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. However, it is not common to have devices monitoring PM10 at indoor places yet. 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. An example is defining the lower control limit for 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 wear lighter clothes at home as they can adjust the temperature there. A solution should be flexible enough to adapt to these common situations.

Processing the data collected through monitoring devices or APIs is another issue of the *Environmental* indicators. Some metric units are well known, like the ones for temperature (°F or °C) and humidity (%). However, the metric unit for measuring PM2.5 and PM10 (ug/m^3) is less known and people usually cannot interpret what it means. Hence, it is important to define how this information is shown. Following the same example, an option is showing the air quality band (1-10) and its description (Low-Medium-High) for the levels of PM2.5 and PM10. Nevertheless, choosing the right standard (e.g. the COMEAP standard for UK [71]) to define the air quality bands to use is another issue to deal with.

The *Internal* indicators refer to physiological indicators, like heart rate and lung capacity. However, it 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) [72]. An important characteristic of the *Internal* indicators is that they can be associated with symptoms (e.g. lung capacity) or triggers (e.g. stress level). The processing of the data is also important for these indicators as users need 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 & Time* dimension (*L+T*), from a software development perspective, is the most relevant context dimension to handle as it makes possible to deliver most of the preventive features. It is critical for a solution to establish the location of a person at a specific time for warning them when they are exposed to hazardous environmental conditions. The relationship of *L+T* with the *Internal* indicators evidencing the appearance of symptoms is important because knowing the places where and times when a person usually presents symptoms is useful in several situations. For instance, it aids to know if a person is monitoring the wrong indicators or the wrong places. The link of the *L+T* dimension with the *Communication* and *Medication* ones is explained below where the latest two are described.

The *Communication* dimension allows stakeholders to be actively involved and provide support in preventive and emergency situations. They can be granted with one or more of the following permissions. The *Check Status* permission allows a stakeholder to see the indicators as regards to the health status of the person with asthma, providing access to the *Reporting layer* (Fig. 2). This permission can be granted, for instance, to a nurse needing to check health information. Stakeholders with *Notifications* authorisation are notified 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 could be granted with this authorisation. Stakeholders with the *Emergency* permission receives emergency alerts when the person confirms that is 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 are examples of people that could be granted with this permission.

The relationship between *Communication* and *L+T* 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 go and help them. The IT literacy and preferences of the person to contact should be considered. Hence, the solution should allow to personalise how to reach the stakeholders automatically. Some options that were highlighted in the *Interviews* and *Personalisation questionnaire* are: SMS, other messaging service (e.g. WhatsApp), emails, notification on their smartphone, and even automatic calls when there is an emergency.

The *Medication* dimension includes the pharmacological strategy of an asthma management plan. People with asthma usually go through a stepwise approach until finding their optimal pharmacological treatment. They move up or down between these levels/steps until finding out the most suitable one for them [3, 2]. This pharmacological strategy must be personalised and, although there are applications providing services for medication management (e.g. Ref. [73]), it is important to include 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.

The benefit of building the relationship between *L+T* and *Medication* was highlighted by the expert in respiratory conditions that was interviewed. It refers to being able to know the places where patients use their rescue inhaler more frequently. This inhaler is used when they have an exacerbation. It is a good indicator to know the times and places in which they usually feel unwell in order to warn and suggest monitoring those places. Efforts on creating automatic counter inhalers relating them to the location where they are used have been made (e.g. Ref. [31]). This article proposes to use the *Medication* dimension in a more comprehensive way by linking it to the *Communication*, *Physiological* and *Environmental* dimensions through the *L+T*. Thus, more meaningful information of the medication usage can be obtained.

4.2. Using ADAPT to describe a real case study

ADAPT is used in this section to describe the context of three people with asthma as an illustration of how the approach facilitates personalisation. They are the participants of the experiment that is reported in section 5.3. The participants have dealt with the condition for a relevant time, so they know their condition properly. They are 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* have mild asthma, and *Person B*'s asthma is moderate. The data was collected through interviews.

ADAPT context dimensions are used to represent the context of the participants that is related to the management of their asthma. This representation shows how a C-AR solution can use the approach to provide services fitting users' needs better. Table 2 presents ADAPT context dimensions shaping the context of the participants and providing enough flexibility to describe the information that is relevant to their asthma management. The *L+T* dimension is not explicitly shown as it is a real-time changing dimension, however, it is the key to exploit the information described by the other dimensions.

The capability that ADAPT provides to monitor different indicators at different places of interest can be highlighted from table 2. *Person B* chose to monitor indoor indicators at University that are different from those that were chosen for 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 track the outdoor humidity nearby the University area as it would be cognitively easier to monitor.

The *Communication* dimension in table 2 shows the people the participants would like to involve and how they would like them to be involved. It evidences the customisability ADAPT allows to include their stakeholders and the privileges that can be granted to them. The approach considers that the stakeholders and their roles could change. This case study highlights this flexibility by showing how the participants chose different roles and privileges in their *Communication* dimension. The flexibility is also evidenced in the other dimensions.

5. Context-aware reasoning and case-based reasoning for personalised asthma management

Non-pharmacological strategies of asthma management plans are related to taking preventive measures for avoiding situations that may be dangerous [2, 3]. For this, a person with asthma shall know their triggers, which is difficult to achieve given the heterogeneity of the condition. Moreover, even if they gain enough knowledge about their triggers, there are still some situations in which they would go through similar difficulties. When this happens, people with asthma shall go again through the trial-and-error process of discovering their new triggers. This uncertainty stage is dangerous because a person can experience a life-threatening attack even if their asthma severity level is the lowest [74]. Hence, being able to assist them during this stage is very valuable as it can be a life-saving feature. Asthma UK states that 3 out of the 4 daily deaths from asthma in the UK in 2015 could have been prevented [75].

CBR can be used with C-AR to provide support in the uncertainty stage by creating cases representing the knowledge of previous situations people with asthma have been exposed to. This is studied based on the idea that using both concepts can create synergies to solve problems dealing with evolving context adaptation [14], and adapting health procedures and strategies to personal constraints defined by contextual information [76]. Techniques needing high amount of data to provide support in the uncertainty stage were discarded because there is not enough available monitoring data representing cause-effect situations of the exposure and symptoms of people with asthma at this stage. Further, even if there were enough available data, it would not be possible to use it with certainty because of the heterogeneity of asthma. This means that the data that is useful for a specific person is likely to be useless for another one because they are likely to be different.

Table 2: 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 fact that CBR creates a personalised database of cases for a specific person makes it more suitable to provide support in the uncertainty stage. The following part of this section explains some concepts needing clarification to understand the CBR cycle for personalised asthma management, which is used to provide support in the uncertainty stage, and its relationship with the C-AR monitoring process. Figure 4 supports this explanation by presenting a class diagram illustrating the monitoring process of a system built based on ADAPT. The figure also represents the inclusion of the communication and medication dimensions.

The classes Trigger and Symptom represent the triggers (e.g. low temperature) and symptoms (e.g. wheezing) a patient may have. The relationships between these classes and the class Patient represent the triggers and symptoms of each patient. 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 linked to indicators like minimum temperature 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 indicators that can be linked to it in the monitoring process. This idea is represented in Fig. 4 by the relationships between the classes Trigger_Indicator and Symptom_Indicator, and the classes Trigger and Symptom, respectively.

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 are connected to their triggers and symptoms, however, their values represent facts that need to be interpreted. The class SI_Measurement represent the monitoring process of the symptoms-related indicators, which are objects of the class Symptom_Indicator that also has the control limits to use in the monitoring process. The monitoring of the triggers-related indicators is represented by TI_Measurement. This monitoring process is different because the triggers-related indicators are usually linked to the places of interest (class Place) that are included in the monitoring process. The association class Control_Limits has the control limits of triggers-related indicators at each place of interest that is monitored.

The location *Location & Time* dimension is included in the monitoring process. The locations is stored as coordinates and it is included in SI_Measurement to record where the person reports symptoms. For the triggers-related indicator, the location of each place is stored, however, the location is also included in the TI_Measurement for when the system monitors the surroundings of the person with asthma (e.g. through a mobile phone using the Google Awareness API). As this type of monitoring process does not consider a fixed place, the system will then store the location related to the measurement that was taken. When the system monitors a fixed place, the location attribute of the

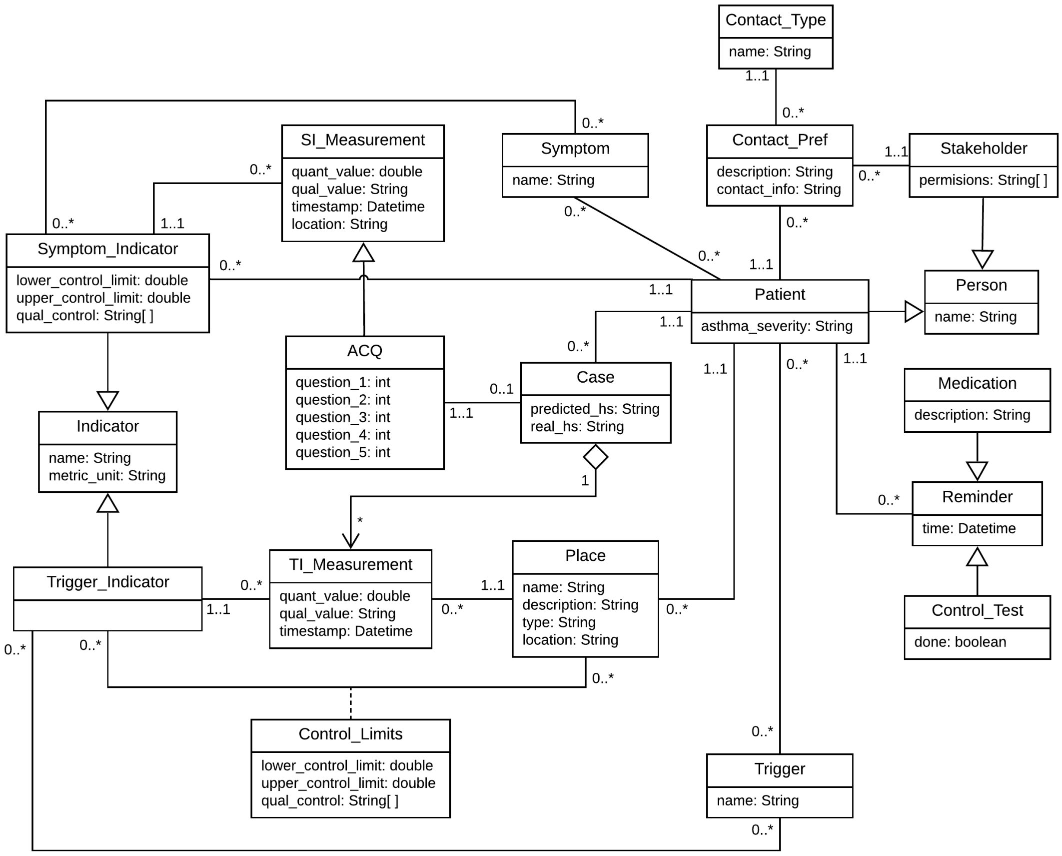


Figure 4: C-AR monitoring and CBR for personalised asthma management

TI_Measurement class is null. The real-time location of the person is not included in this class diagram. Nevertheless, the real-time location of the person is constantly tracked for being able to exploit the monitoring process data and deliver preventive and emergency services.

The monitoring process considers quantitative and qualitative values. For instance, a person would like to monitor the temperature of a specific park, so they can set the lower control limit (e.g. 12° C) in the Control_Limit related to that park. Nevertheless, they would also like to monitor qualitative weather characteristics (e.g. windy, rainy), so it is possible to specify this type of data in the qual_control attribute, which is an array of strings. For this, TI_Measurement also has a qual_value attribute that is comparable to the qual_control attribute. The same can also be done for the symptoms-related monitoring process, if it is required by the user.

A case for a CBR supporting asthma management (C_x) is made of a set of pairs indicator-value 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 or pollen level). A case that will be used for asthma management is described by equations 1 and 2. The class Case and its relationship with TI_Measurement illustrate how the I_x of the cases are built. The attributes predicted_hs and real_hs of the class Case represent hsp_x and hsr_x. The class ACQ is a subclass of SI_Measurement that represents the answers to the Asthma Control Questionnaire, which is used to define the real_hs or hsr_x of a case. The ACQ and its application are better explained in section 5.3.

$$C_x = \{I_x, hsp_x, hsr_x\} \tag{1}$$

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

Figure 5 presents the CBR cycle for personalised asthma management. It was created based on the CBR cycle proposed in Ref. [77]. 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, 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 (hsr_x) in the *revision* phase, and C_x is completely defined. Finally, C_x is *retained* by storing it in the database of previous cases. The synthetic evaluation of the CBR cycle for personalised asthma management can be found in Ref. [65]. Section 5.1 explains and provides a solution to the issue of fitting the C-AR component of a system built based on ADAPT, in the CBR cycle for personalised asthma management.

The asthma health status is linked to the asthma-related symptoms a patient shows. It can be measured in different ways. For instance, devices measuring breathing rate and blood oxygen level can be used to determining the health status of a person. In this research work, the asthma health status of a person is determined through the ACQ, which has been validated for being used in clinical settings. Thus, the Class Case is associated with the class ACQ. If the asthma health status of a person was determined using devices measuring their symptoms, the Class Case would be associated with SI_Measurement to define real_hs.

The outcome of applying the ACQ is a real number acq, $0 \leq acq \leq 6$. The acq has a binary interpretation represented by function 3, where 1 refers to deteriorated (or not well-controlled) health status, and 0 to a normal (or well-controlled) health status. The acq could be disaggregated into more classes for providing information about the severity of an attack. Nevertheless, a new classification of the acq with more granularity would need a thorough validation before using it. The binary classification used in this research work has been properly validated in [78, 72].

$$f(acq) = \begin{cases} 1 & \text{for } acq \geq 1.5 \\ 0 & \text{else} \end{cases} \tag{3}$$

The CBR cycle for personalised asthma management (Fig. 5) uses CBR to attempt predictions based on cases representing old experiences of a person. Following the trends of CBR application (section 2), multimodality is proposed to aid the CBR monitoring. A person with asthma may partially know their triggers, so they can set some rules (control limits) based on the monitoring process ADAPT context-dimensions allow to personalise but they could still use CBR to aid them with their unknown triggers. Thus, some elements of I_x can be assessed by previously set rules, but others can be assessed following the CBR cycle. This balance between C-AR and CBR is presented in section 5.2.

This research work also brings to attention others uses of CBR in asthma management. CBR can assess similarity among people with asthma, which allows reusing cases of different people. This *"interchangeable CBRs"* idea refers to reuse the cases of another simi-

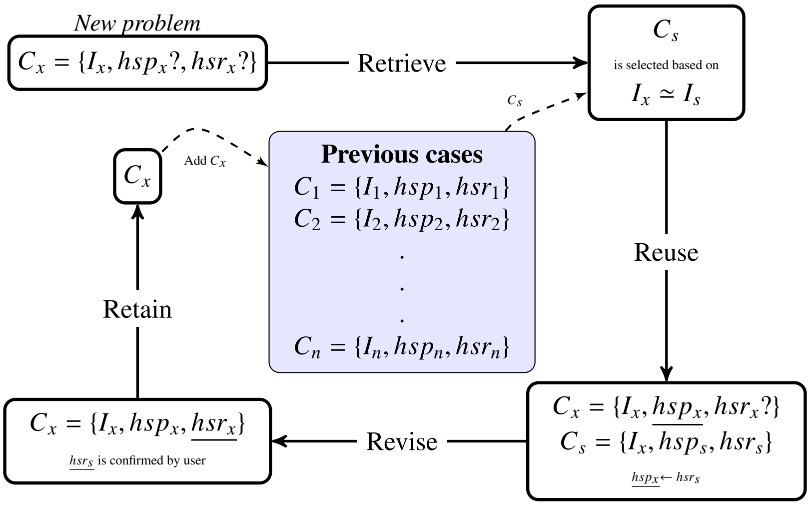


Figure 5: CBR cycle for personalised asthma management [65]

lar person with asthma in order to accelerate the learning curve of the CBR. Considering this, CBR can help in selecting the most similar person with asthma whose database of previous cases can be reused. This similarity assessment of people with asthma would also allow more experienced patients and carers to share already known monitoring rules about their condition with less experienced ones. These ideas are explained as future work in section 8.5.

5.1. Context-aware reasoning and case-based reasoning interaction

The interaction between the system components implementing the C-AR and CBR strategies must be carefully designed. Figure 5 shows the cycle the CBR component performs. The C-AR 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. The formalisation of this interaction is defined by 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. 5. The role played by 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 sensors or virtual sensors (like 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 [16]. 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 [79].

The CBR then *retrieves* the C_s for *reusing* hsr_s to determine the hsp_x of C_x. C_s is the previously stored case that has the most similar I to I_x. Although the application example presented in section 5.3 uses the Nearest Neighbour for the similarity assessment between two I, other algorithms can be used. The elements of I were normalised, and a weightless comparison was done for this research work. Section 5.3 provides more information of the similarity assessment.

C-AR also plays a key role in the *revision* stage. Here, after *reusing* the solution of C_s, the person has to confirm whether the predicted solution is accurate or not by assessing their asthma health status. C-AR is used here to collect the real asthma health status. The ideal collection 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 also heterogeneous. Further, monitoring just one indicator (like heart rate or breathing rate) is not enough as it may vary not only because of asthma-related reasons. This makes this task more complex as several indicators should be monitored and compared to build higher-level contexts and determine someone's asthma health status accurately in real-time.

Two ways of determining the real asthma health status of a person to complete the *revision* stage are considered in this project. The first one is through the Asthma

Control Assessment Component (ACAC) that is used to monitor the health status of people with asthma. More details of the ACAC are provided in section 5.3. The second one is the use of a VA that interprets the user's voice commands and detects if their asthma health status is normal or deteriorated based on their commands. Section 6 provides a detailed description of the VA.

C-AR has another relevant task to perform between the *revision* and *retain* stages, which is deploying 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. 2) and is related to their *Communication* context dimension. 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. The novelty of using C-AR together with CBR to predict someone's asthma health status is the main reason of the decision to use a more conservative approach to deliver these notifications.

Algorithm 1 Interaction between 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 starts personalised notification protocol.
end if
C-AR sends $hsr_x$ to CBR.
CBR uses $hsr_x$ to revise and complete $C_x$.
CBR retains $C_x$.
```

5.2. Balancing the use of case-based reasoning

This section presents three scenarios representing the three potential situations of a person with asthma. The way of using C-AR and CBR for each scenario is explained. The scenarios are summarised in algorithm 2.

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 first two scenarios refer to extreme situations. The first one 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. The second scenario is a person not knowing their triggers (uncertainty is the highest possible). In this case, the CBR component attempts the prediction of the person's asthma health status. The C-AR component then performs all its functions (e.g. collecting data to create cases or alerting when there is a risk) but the real-time analysis of the indicators.

The third scenario is a hybrid situation in which the person partially knows their triggers but there are still some that have not been discovered. For instance, they might know that low temperatures is their trigger but they still have exacerbations even without being exposed to low temperatures. In this situation, multimodal reasoning is used. The C-AR component analyses those indicators with monitoring control limits previously configured by the user, and the CBR one is activated to predict hazardous situations.

5.3. Application example: a real case study

This section reports on the evaluation of using C-AR together with CBR to predict the asthma health status of a person in a real-life scenario. The three people with asthma that were described in section 4.2 took part in this experiment. They used a mobile application that partially monitored their environmental exposure, and that also implemented the ACAC as the tool they used to monitor their asthma health status. Thus, the mobile application collected the environmental data required to create the cases to be assessed in the CBR cycle (Fig. 5), and the real health status associated with the cases to complete the revision stage. The system did not deliver alerts when it detected a hazardous situation. This was an ethical decision aiming to protect the participants from the risk of delivering false positives that would increase their stress level, which is a potential trigger that would provoke or worsen an asthma attack.

The mobile application, which was built using Android Studio, was adapted to perform in their smartphones. The monitoring feature was built using the Google Awareness API that allows to monitor some specific outdoor environmental indicators considering the real-time location of the smartphone [80]. The following triggers-related indicators were collected by 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 were asked to use the ACAC at least once a day to monitor their health status. The usability of the ACAC, which implements the daily version of the ACQ, was previously evaluated in Ref. [69]. The answers to the ACQ referred to how they felt that specific day, so its outcome was associated with the real health status for that 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 did not use the ACAC, then the case created for that day was discarded as it was not possible to know the accuracy of the prediction nor reuse that case for future predictions.

The I_x of a case representing the conditions of a specific day is made of the max. and min. temperature, max. and min. feels like temperature, and max. and min. humidity the participant was exposed to in that day. I_x also includes the max. and min. PM10 values at a specific place in that day. It was not possible to collect the PM10 values using the location of the participants' smartphones as there is no service providing these values at the locations the participants performed their activities. A place that was close to the their work place and in which PM10 was able to be monitored was chosen. The participants were not allergic to substances that are monitored through PM10, so it is expected this choice not to have influenced in the results of the experiment. The London Air Quality Network [81] was used to monitor the PM10 values at Enfield, London.

The I_x of the cases were normalised to use a scale going from 0 to 10. This was done to force a weightless comparison of the indicators in the *retrieval* stage (Fig. 5, algorithm 1). The experiment evaluates the use of C-AR and CBR when the uncertainty level is the highest possible (algorithm 2), so a weightless comparison is more appropriate to evaluate the performance of the CBR component without including previous information about the participant's triggers. The Nearest Neighbour algorithm was used in the *retrieval* stage to select C_s. The calculation of $d(I_x, I_s)$ was based on the Euclidean distance. The attributes that were included in the calculation were the environmental ones that were specified above. The Euclidean distance was chosen because of the good performance it showed in the synthetic evaluation [65].

Person A assessed their health status during 51 days but their health status was not reported as deteriorated in any of these days. The accuracy score for this person was 100% as only cases representing normal health status were generated. This shows that using C-AR and CBR in this situation does not deliver false positives.

Person B assessed their asthma status for 40 days but only 32 cases were generated because there was not enough 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 cannot predict if there are no previous cases to use. The final cumulative accuracy for Person B was 70.97%. The behaviour of this cumulative is shown in Fig. 6.

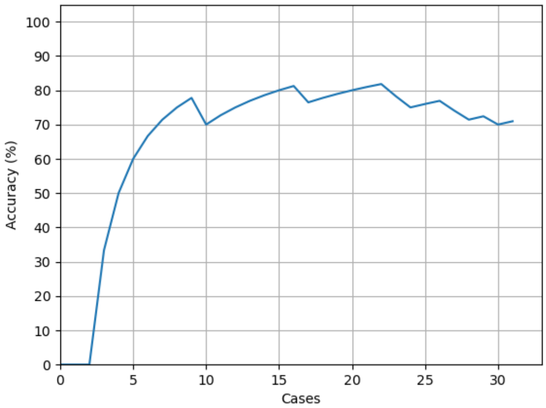


Figure 6: CBR evaluation: cumulative accuracy for Person B

The mobile application was adapted for Person C as their asthma is triggered by demanding exercises. The level of demanding exercises is difficult to measure because it is a higher level context that is the result of several indicators (like distance, time, heart rate, etc.) that are assessed when a person is performing certain activities. For this experiment, one simple question was added, which asked Person C to rate from 0 to 10 how demanding the exercises they did during the day were.

Person C assessed their asthma health status for 59 days. Nevertheless, 7 cases were discarded because there was not enough environmental data available to complete the cases for those 7 days. The results for this participant are based on 52 cases representing 52 days. The case representing the first day was not included in the assessment of the accuracy. The cumulative accuracy for Person C was 90.20%. Figure 7 shows behaviour of the cumulative for Person C.

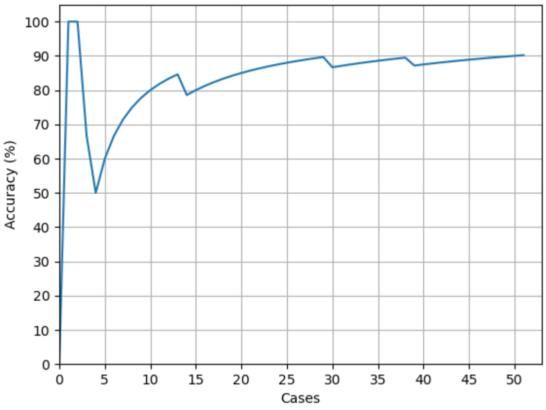


Figure 7: CBR evaluation: cumulative accuracy for Person C

Table 3 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 should have been classified as *Normal*, how many of these cases were correctly classified as *Normal*, and the accuracy for classifying these cases. This explanation is also valid for the *Deteriorated health status* columns.

Table 3 shows that Person C had more normal cases to classify (40 cases, 78.4%), while Person B had more deterioration cases (18 cases, 64.5%). The accuracy, considering that the data is imbalanced, was 67.52% for Person B and 87.16% for Person C. The results for Person A are different because they never experienced a deteriorated health status.

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

This section presents the development and validation of a VA that facilitates the application of C-AR and CBR for personalised asthma management that was explained in section 5. The architecture and sequence diagrams of the system implementing these technologies is explained (section 6.1) to show the technical perspective of its performance. Section 6.2 provides details of the experiment that was done to validate the text classifier.

6.1. System architecture

The architecture diagram highlighting the interaction among the VA, the C-AR and the CBR components is shown in Fig. 8. It does not represent the whole system explained in Fig. 2 as it does not include the *Personalisation* and *Reporting* layers. The diagram illustrates the use of VA for the specific purpose of confirming and completing a case with the real health status of the person in the *revision* stage. VA for personalised asthma management could also be used to enhance the functionalities of the system in other situations (e.g. asking for a specific report considering the user's personalisation), but these are not part of this case study.

The VA is represented by the *Speech-to-Text (S2T)*, *Text-to-Speech (T2S)* and *Text Classifier* elements. The first one is transforms a voice command said by the user into text. The second one gets a phrase (text) and transforms it into a voice command that can be delivered to the user. The *Text Classifier* interprets the phrase the user said into *normal* or *deterioration* state. The VA enhances the HCI component of the proposal by providing the user with an alternative to the ACAC.

The *CAR* is the main component of the system as it transforms the collected contextual data (from the *Data Handler* or *VA*) into meaningful data the *CBR* can process. Once the *CBR* makes a prediction, the *CAR* also notifies the user of the prediction, and asks them to confirm their health status for completing the CBR cycle.

6.2. Training and validation of the text classifier

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 chose the symptoms they experience when their health status is deteriorated (see table 4). The phrases were created to represent the five most common symptoms chosen by the respondents.

Table 3: Comparison of the results for Person A, Person B and Person C

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	22	70.97	13	6	46.15	18	16	88.89
Person C	51	46	90.20	40	37	92.50	11	9	81.82

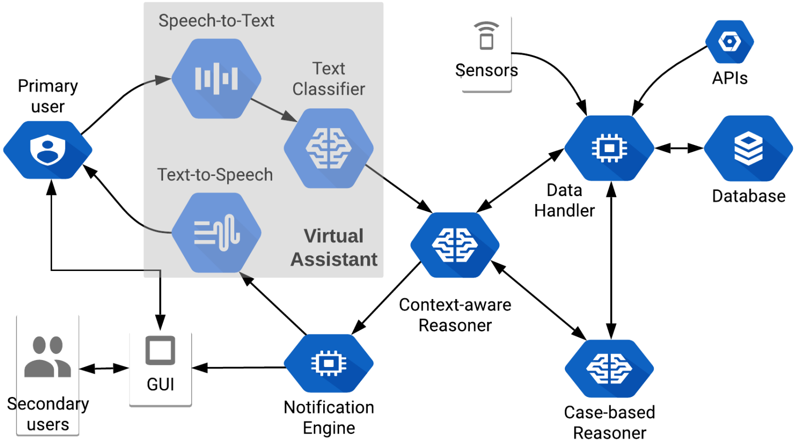


Figure 8: Architecture diagram of the system

The creation of the phrases was also supported by some keywords that were used by the participants that were interviewed in the initial stage of the project. Thus, other more general phrases (like *"My asthma is bad"* or *"My health is not OK"*) were also included for allowing the use of 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. [82].

The *Text Classifier* training and validation were done using Python Scikit-learn library [70]. The *bag of words* concept was used to transform the phrases into vector features that were then assessed by the Scikit-learn classification algorithms. The algorithms showing best results in the training were the Random Forest (100%), Nu-Support Vector (98.36%) and Decision Tree (100%) classifiers. The validation involved people with asthma that were asked for the phrases they would use to express that their asthma health status is *normal* or *deteriorated*. This was done through a questionnaire that was spread through the Asthma UK Patient Advisory Group. From the 107 phrases that were collected (18 respondents), 43 phrases refered to *normal* and 64 refered to *deteriorated* health status. The phrases used for the validation can be found in Ref. [83]. The phrases have been improved by fixing some typos. Only 103 phrases are shown because duplicates were removed.

The outcomes of the training and validation are shown in table 5, which presents the accuracy obtained in each process. The Nu-Support Vector Classifier algorithm incorrectly classified less phrases (17/103), while the Random Forest and Decision Tree algorithms incorrectly classified 18/103 phrases. Fifteen (15) of the incorrectly classified phrases are common to the three classification algorithms. The phrases that were incorrectly classified can be found in Ref. [84].

The case study presented in this section was chosen as an example to show how VA can be used as an alternative way of performing a specific task. The case was used in the validation of ADAPT (section 7).

7. Validation of ADAPT

ADAPT was validated with real users who 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, using the Likert scale (very useless - useless - neutral - useful - very useful). The questionnaire also included

Table 4: Symptoms ordered by number of respondents

	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

Table 5: Text classifier: accuracy of the training and validation

Classification algorithm	Training	Validation
Random Forest	100%	82.52%
Nu-Support Vector	98.36%	83.50%
Decision Tree	100%	82.52%

open questions asking them to explain their reasons to choose their quantitative answers, and to provide feedback about how to improve the system. Another question asked to rank the features from the most important to the least important in order to assess what elements of ADAPT were perceived as more or less important by the users. The questionnaire can be found in Ref. [85].

The participants were recruited through Asthma UK Patient Advisory Group. The experiment was designed for being done through face-to-face sessions and remote meetings using Skype for video conference. Vysor (www.vysor.io) was used to share the screen of the smartphone in which the prototype was installed, for 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. It was possible to recruit 8 participants for the face-to-face meetings, and 2 for the remote sessions. The participants were 6 people with asthma, 2 experts in respiratory conditions, 1 non-professional carer, and 1 person with asthma/non-professional carer. The individual sessions lasted between 50 and 80 minutes.

7.1. Description of the prototype

The prototype implements six main features: personalised monitoring (PM), communication (CO), triggers assistance (TA), control test management (CTM), virtual assistant (VA), and medication reminder (MR). Table 6 shows the most relevant relationships among the main elements of ADAPT (columns) and the prototype features (rows). The *location-time (L+T)* context dimension is less explicitly shown in the prototype than the other dimensions because it is mostly implemented in the background activities the prototype executes.

The PM feature allows to monitor the environmental indicators at the places of interest. It also monitors the internal indicators chosen by the user, and delivers alerts to people chosen by the user through the CO feature, which permits to choose the people to involve in the asthma management process. The L+T 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 is also linked to this feature because it sends a warning as a notification to the people chosen by the person through the CO, when the CBR detects and confirms a hazard.

The triggers assistance (TA) feature is linked to the environmental, internal, communication and L+T context dimensions in a similar way than the PM feature is. The TA feature implements the CBR cycle for personalised asthma management and its interaction with the C-AR component (section 5). The CTM feature keeps track of people's asthma health status (internal context dimension) through the ACAC. The CTM also associates the outcome of a control test to the location where and time when it was done, and allows the creation of control test reminders that are shown as notification (or alarms if the user chooses this option). When the TA feature is activated, the outcomes of the control tests are linked to CBR cycle in the *revision stage*.

The MR feature allows to set reminders that are shown as notifications or alarms. This feature fulfils one of the requirements gathered in the *personalisation questionnaire*. The VA implemented the feature explained in section 6. The use of VA is a complement to the other features of the system, which means that its application can be expanded. The triggers and symptoms context dimension is not included in table 6 because it was implemented as an informative component allowing users to choose their triggers and symptoms from a list. 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.

Figures 9-12 show some screens of the prototype. Fig. 9 is the main screen of the mobile application. Each option of the main screen is not linked to only one spe-

Table 6: Prototype description: features implementing the main elements of the proposal

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

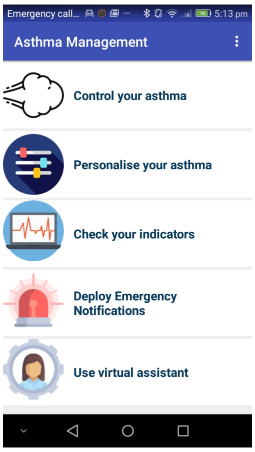


Figure 9: Main screen

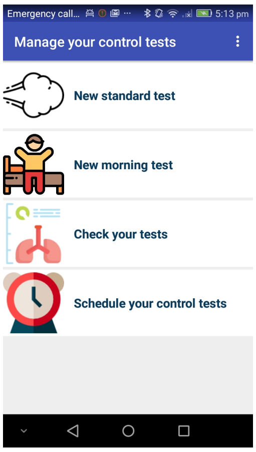


Figure 10: CTM screen

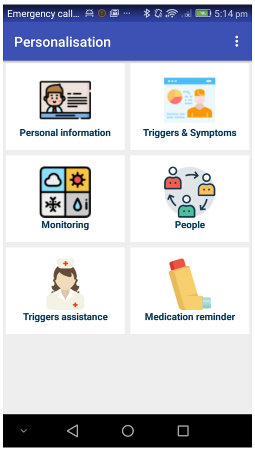
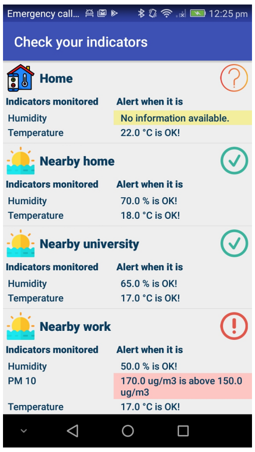


Figure 11: Personalisation



Home

Indicators monitored	Alert when it is
Humidity	No information available.
Temperature	22.0 °C is OK!

Nearby home

Indicators monitored	Alert when it is
Humidity	70.0 % is OK!
Temperature	18.0 °C is OK!

Nearby university

Indicators monitored	Alert when it is
Humidity	65.0 % is OK!
Temperature	17.0 °C is OK!

Nearby work

Indicators monitored	Alert when it is
Humidity	50.0 % is OK!
PM 10	170.0 ug/m3 is above 150.0 ug/m3
Temperature	17.0 °C is OK!

Figure 12: Report example

cific feature. The features are distributed throughout the five options. For instance, the *Control your asthma* option takes to the screen shown in Fig. 10, 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. 11. Here, the *Triggers assistance* also allows to set up the frequency of the control tests (CTM) in order to create the cases for the CBR component.

The PM feature has to be configured before delivering personalised reports and notifications. This is done by choosing the *Monitoring* option from the screen shown in Fig 11. 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 monitor. The mobile application uses this configuration to show personalised reports, like the one shown in Fig. 12. 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 taps on the notification, the mobile application takes them to the personalised report (Fig. 12).

The PM feature is based on the configuration done by the users depending on the characteristics of their condition. However, as explained before, this configuration cannot be done when a person with asthma does not know their condition properly. The system, besides the TA feature, aids recently-diagnosed patients by showing guidelines they can use to set the control limits of the indicators to monitor. The user can select an indicator to monitor and the system shows them the option to consult a guideline with recommended control limits for that indicator. The prototype implemented this guideline for some triggers (temperature, humidity, PM10, PM2.5) to show the participants how this option works. These control limits can also be set based on the advice provided by a nurse/doctor in the consultations.

The *Personal information* and *Triggers & Symptoms* options in Fig. 11 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 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 4.1). Once this is configured, the user can reach the people chosen to be contacted in emergency situations using the *Deploy*

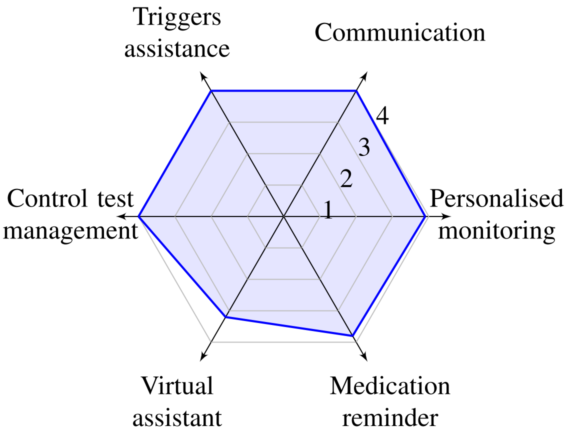


Figure 13: Perceived usefulness of the prototype features

Emergency Notifications option from the main screen (Fig. 9). The option must be available even on a locked screen, so it can be used faster in case of emergency.

The CBR cycle for personalised asthma management is used when the *Triggers assistance* option (Fig. 11) is activated by the user. The system can execute the *monitoring* and *triggers assistance* options at the same time or individually in order to balance the usage of C-AR and CBR according to algorithm 2 (section 5.2). The *Medication reminder* option (Fig. 11) allows to configure reminders to take their medication. Finally, when the *Use virtual assistant* option (Fig. 9) is chosen, the VA is activated to interact with the user. Ideally, the VA shall be part of the native VA of the smartphone.

7.2. *Results of the validation*

The average of the answers to the questions assessing the usefulness of the prototype features are summarised in Fig. 13. The center of the spider web diagram represents the value of 0 that refers to the answer *very useless*. The value of 4 is assigned to *very useful*. The features TA, CO and CTM were assessed as very useful by all the participants, so their average assessment was 4. The PM feature (average of 3.9) was assessed as very useful by all the participants but one who assessed it as useful. The MR (3.8) was assessed as very useful by all the participants but two who assessed it as useful. Finally, the VA feature (3.2) was assessed as very useful by three participants, as useful by six, and as neutral by one.

Table 7 summarised 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 feature assessed as the least important. Thus, the average column reflects the average of the answers given by the participants. The CTM feature was the highest-ranked (2.2) and the VA feature was the lowest-ranked (5.4).

Table 7: Ranking of the prototype features

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

The analysis of the answers to the open questions for each feature is presented in the order of table 7. The CTM was the feature with the highest perceived usefulness and rank. The points the participants liked more 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 for improvement are: generating graphical summary reports of the outcomes, make the reports available to professionals, improve the design, create a version for children, reports linking the results to exposure, and being able to enter/calculate their personal best peak expiratory flow (PEF).

The second highest ranked feature is the PM. 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 for the users to know the indicators to monitor better.

The TA feature was perceived as a very important preventive feature. Two participants even agreed on it being 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 refers to provide reports summarising the data gathered through this feature, improving the explanation of how to use it, sharing the data with professionals, suggest possible triggers from the data. One person showed concern for the accuracy of the feature, considering some people's asthma might be triggered by emotional stress.

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

The MR feature was assessed as relevant for those with poor medication management habits. The fact that medication not only related to asthma can be added was recognise positive, as well as its easiness to use. The main suggestion was about confirming the medication was taken. Some participants wanted to include the dosage of their medications and keep an inventory to have reminders to buy medicine. Including diet management was highlighted as important by one expert.

The VA feature was the lowest ranked. Participants perceived this feature as helpful for those familiar with VAs, however, only one of them affirmed to use VAs regularly and recognised it as a technology that most people use nowadays. Four of them said that using a VA 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 VAs usually do not recognise their accent as a justification to avoid this technology. One participant suggested to ask the ACQ through the VA in order to have a better quality assessment. Moreover, two of them suggested to define a phrase that the VA can recognise as emergency, one recommended to use the VA to record a diary of the triggers and symptoms they experience. One extra question about the VA 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 VA 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 (not specific to a feature) was also collected. The suggestions are: giving a name and a better icon to the mobile app, making all collected data available to professionals/researchers, and adapting the prototype for people that take care of more than one person with asthma. The questionnaire did not include a question asking about the positive points of the system, however, three of them wrote down comments highlighting the comprehensiveness of the mobile application as a solution covering all the key points they would like to manage about their asthma.

8. Discussion

This section presents the discussion about the research work. The benefits, opportunities and challenges are shown. Future work is suggested to improve the system and address some issues brought by the research.

8.1. Personalisation

ADAPT supports the development of personalised C-AR solutions addressing the heterogeneity of asthma management. The cases study presented in the article show that ADAPT supports personalisation in a comprehensive way and at different stages of the asthma management process. ADAPT context dimensions can properly describe people with asthma with different characteristics, which is important as it facilitates the design and delivery of useful services. The dimensions help in preventive and reactive situations using and delivering information that can help in decision-making.

The context of a person with asthma is challenging to monitor. 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, however, there is not a generalised used of them yet, and the availability of their data is usually 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 Chronic Obstructive Pulmonary Disease. The integration challenge of C-AR from an Internet of Things perspective [16] must be carefully addressed in order to create this kind of networks.

The interaction of the C-AR and CBR components to predict someone's asthma health status is an important part of ADAPT. 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 it if they are overloaded with irrelevant notifications. This frequency is especially relevant to define when the database of cases is still not representative enough. This frequency should also be personalised by the user, however, they should be aware that the more cases they create, the more accurate the CBR algorithm is expected to be.

8.2. The location-time context dimension

The L+T is very important in the creation of solutions built based on ADAPT. Determining the location of a person with asthma at a specific time directly impacts on the performance of the C-AR component of the solution. The L+T also impacts the creation of the cases for the CBR component. The L+T operatively connects the information of the other context dimensions. Thus, a system implementing ADAPT must precisely determine 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 their exposure. 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 frequent as a place to monitor, however, if the person is currently at their workplace, which is far from that park, the system should present the park as a potential hazard if the PM10 levels are high there. Nevertheless, if the person is walking nearby the park, then the system should present the park as a real hazard. This characterisation cannot be achieved if the system cannot determine the current location of the person.

The cases for the CBR have to be built considering the L+T dimension as it is key to determining someone's real exposure. The cases are built based on the indicators the C-AR component monitors. This monitoring process can take place at different locations (e.g. workplace, home) 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 their exposure. If the L+T is not included in this process, the cases will not then represent the exposure of the person and the accuracy of the CBR component will be affected.

Technology tracking location through GPS is already established in the market, and it is broadly used in mobile technology. The experiment reported in section 5.3 successfully used this technology to partially monitor the participants exposure. Nevertheless, technology for determining someone's indoor location is still not established in the market, despite the research efforts done on this subject (e.g. Ref. [86, 87, 88]). Indoor localisation capabilities would be useful for people spending relevant time in large indoor places that have rooms/areas with heterogeneous environmental characteristics.

8.3. Real-time analysis and predictions

ADAPT facilitates decision-making in asthma management, which implies to deliver services allowing the analysis of past, present and future situations. ADAPT addresses this issue putting special emphasis on the personalisation required for asthma management plans.

The preventive state of a system should analyse current and possible future contexts of a person. The current context can be analysed when the values of the monitored indicators are available. The analysis of possible future contexts is more complicated as it requires having access to the forecasts of the indicators. Some of these forecasts are easy to access (e.g. weather) but others are still not as reliable, broadly accepted nor accessible (e.g. PM 2.5 or PM 10). Supporting people knowing their triggers is less complex as their context analysis relies on the personalisation they do about the indicators to monitor. A set of if-else rules obtained from this personalisation, which define the analysis of the C-AR component (Fig. 2 Context layer), are used to perform the real-time analysis. When it comes to support people not knowing their triggers properly, the CBR component needs to know how to deal with not enough information to complete the cases to evaluate.

Dealing with incomplete information is highly possible to happen in a real scenario. Incomplete information increases uncertainty and affects decision-making. This situation is easier to handle when ADAPT supports people knowing their triggers. In this case, the system can do the analysis based on the available information. For instance, if the system cannot obtain the forecast for next day temperature, it should then inform users about the unavailable data. The CBR component must be designed to know what to do when there is not enough information to complete a case. This should be further investigated but some options are suggested here. One is to replace the missing values with historical information. Another is not analysing the incomplete case. The third one is to do the similarity assessment of the CBR cycle considering only the indicators with non-nullified values of the new case to analyse. In any case, users must be informed when information is missing.

ADAPT considers that the person with asthma can create cases at any time. This is challenging because the system needs to define the time frame to select the information that will be used to create a case. This decision depends on several factors. One is the time that has passed since the last time the user assessed their 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 time frame to create a new case. It is better to consider the context related to the day of the assessment. A case should link the asthma health status of the person to the conditions that led to that health status. Hence, the time frame should make the case represent reality in the most accurate possible way.

8.4. Virtual assistant technology

VA is considered as an alternative to facilitate the interaction with the user. This research work studies the use of VA for determining the asthma health status of a person, as an alternative to the ACAC. The non-compulsory nature of a VA is represented in Fig. 2 by the dotted-lines rectangle that is positioned between the system and the user. Section 6 presents a VA aiding in the interaction represented by the arrow going from the *User* to the *Contextual Data* repository.

This research work shows that, in general, people welcome the use of VA in asthma management, however, there is still scepticism about it. The positive points are mostly highlighted by ideas associated with making a system more practical and easier to use in their daily activities. The scepticism is reflected by opinions linked to people not trusting in its accuracy to understand them, and people feeling uncomfortable interacting with a VA. This supports ADAPT proposal of using VA as an alternative for those that are keen on using it.

The participants received in the validation an explanation about the tasks that a fully operative VA for asthma management is meant to support. Most of them agreed with the idea that people *"already using virtual assistant technology for less important things"* is perceived as encouraging. 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"*. Some of the VA applications the participants suggested are: replacing the paper-based peak flow and medication diary, keeping track of what someone thinks has affect them, reminders of to-do tasks, and providing advice when the system detects the appearance of symptoms or hazards. The application of this technology was highlighted as more convenient for people living alone, with problems to remember things, and those recently-diagnosed that need more guidance during their initial stage.

8.5. Future work

ADAPT aids the development of systems with future generation characteristics. As it has been demonstrated through the article, several advances in different fields must be achieved before this kind of systems spread significantly. The development of networks of indoor and outdoor environmental monitoring devices granting access to their data, the hardware and software integration challenges, and mobile devices monitoring physiological indicators reliably are some issues needing to be addressed to spread this type of technology.

The similarity assessment of the *retrieval* stage in the CBR cycle for personalised asthma management should be further studied. This research work used the Nearest Neighbour algorithm and the Euclidean distance to select the most similar previous case to the one that is assessed. Although the results of the experiment were positive, other algorithms and distance measurement techniques between cases may improve this accuracy. The inclusion of more information in the cases for the CBR cycle for personalised asthma management is also suggested as future work. The inclusion of higher-level context (e.g. activity being done during an attack, information about current lifestyle, and so on) to build the cases shall also be further investigated as it is expected to help increasing the accuracy of and the knowledge gathered through the CBR cycle. The degree of severity of the attacks can also aid in decision-making, so more granularity in the classification of the ACQ and the use of PEF readings to define this severity should be further studied for being included in the system.

The outcomes of the research work encourages to investigate other applications of CBR in asthma management. The idea of *"interchangeable CBRs"* to reuse a personalised database of previous cases for other similar patients going through the uncertainty stage shall be further investigated. For this, the database of previous cases to be shared and reused must have been previously proven to be useful for the uncertainty stage.

Choosing a similar person with asthma is another issue in which CBR can also aid. The use of CBR to assess similarity among patients based on EHRs is important to study. This idea not only aids in reusing a personalised database of previous cases, but also in sharing knowledge about the condition among patients, carers and researchers. This can help, for instance, recently-diagnosed people to accelerate their learning curve, people with asthma moving to places with environmental characteristics they have not experienced before, and so on. Sharing data of patients should carefully consider privacy issues. The current system collects anonymised data in the form of monitoring rules and cases reflecting cause-effect situations related to triggers and symptoms. Future work must also allow to share anonymised data.

The implementation of a knowledge layer is another important point to highlight as future work. The system gathers data from heterogeneous sources, implements C-AR and allows to model these data to feed the CBR component. The system was created following a bottom-up approach to address a societal need. Having satisfactory validated the current version of the system, it is important to improve the system in more sophisticated ways. One of the main improvements is a knowledge layer that can use contextual information at different levels to provide support to recently-diagnosed patients regarding their allergens and symptoms, besides the CBR component. This would be useful especially when the CBR has none or few cases. A knowledge layer would also facilitate sharing knowledge from more experts stakeholders with less experienced ones. For this, it is important to include information about allergens and main symptoms observed during attacks.

8.6. Study limitations

The experiment evaluating the CBR cycle for personalised asthma management (section 5.3) in a real-life scenario had some limitations. The information about the outdoor environmental exposure was collected through APIs (Google Awareness, London Air Quality Network) of monitoring networks that were not installed nor controlled by the research team. These networks are available for research purposes. Indoor environmental exposure was not monitored for the participants as this type of devices were not available to be installed in the indoor places the participants frequented. Monitoring indoor environmental exposure is expected to have improve the outcomes of the experiment. PM10 and PM2.5 values were not monitored based on the participants' real-time location. Nevertheless, this is expected not to have influenced the results of the experiments as none of the participants were allergic to substances monitored through PM10 and PM2.5. The participants were not asked to stop their asthma treatments.

The overall ADAPT validation experiment included ten participants from which three also participated in the more specific experiment evaluating the CBR cycle. The fact that this was the first version of the system as well as the first time that C-AR and CBR were used together in the development of intelligent environments encouraged us to give more importance to a qualitative assessment than to a quantitative one.

9. Conclusions

This research work proposed and validated ADAPT as an approach guiding research on creating C-AR solutions supporting the personalisation of asthma management. The personalisation layer of ADAPT, which is the most influential one, is made of context dimensions that cover the key elements to implement the pharmacological and non-pharmacological strategies of asthma management plans. The approach considers CBR as a tool to support people not knowing their triggers properly, which makes it not possible for them to define their customised management plans because of the lack of knowledge about their condition. CBR links their exposure to their asthma health status, and creates cases representing previous experiences that are used to attempt the prediction of their real health status. Virtual assistant is considered by ADAPT as a complementing technology helping to improve the HCI component of a solution supporting asthma management.

ADAPT is the result of the continuous interaction with people affected by asthma. This article explained the elements of ADAPT that were proposed and implemented based on the insights received in the experiments that involved people with asthma, carers and experts in respiratory conditions as participants. The proposal of using C-AR together with CBR to support the uncertainty stage of asthma management was evaluated in a real life scenario involving three people with asthma. The interaction between the components implementing both concepts was formalised as part of ADAPT. A mobile application implementing ADAPT was developed and validated in another experiment. The assessment done as part of the validation included open and close questions asking for feedback about the features of the prototype, which were linked to the elements of the approach. The results of the validation were positive and the points for improvement highlighted by the participants referred to non-fundamental issues that are not related to the usefulness of ADAPT elements. Future work was proposed based on this feedback and the lessons learned from the research project.

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